A RANGELAND WATERSHED MANAGEMENT SPATIAL DECISION SUPPORT SYSTEM: DESIGN, IMPLEMENTATION, AND SENSITIVITY ANALYSIS

by

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ABSTRACT

Watershed management decision making is a complex process. Cooperation and communication among federal, state, and local stakeholders are required while balancing biophysical and socio-economic concerns. The public is taking part in environmental decisions, and the need for technology transfer from public agencies to stakeholders is increasing. Information technology has had a profound influence on watershed management over the past decade. However, as more data and complex applications become available, decision makers are required to have expertise in new domains such as GIS, remote sensing, the Internet, and database management systems. Few watershed decision makers have this expertise and therefore these new capabilities are frequently left out of the decision process.

A prototype spatial decision support system for rangeland watershed management was developed to simplify the process of incorporating advances in technology into the decision process. The application utilizes an open framework by using Web services that are components that

communicate using text-based messages, thus eliminating proprietary protocols. This new framework provides an extensible, accessible, and interoperable approach for spatial decision support systems. An important input into the SDSS is digital elevation data where data are produced using different methods, and with different accuracies and resolutions. Six digital elevation models were compared with survey data to evaluate accuracies at different locations in the Walnut Gulch Experimental Watershed. The sensitivity of the SDSS was evaluated using six management systems that were ranked based on minimizing sediment yield. The sensitivity of the DEM, contributing source area value, and precipitation event size on management system rankings was evaluated. Results provide assistance for users in selecting these data and modeling values. This research illustrated that recent advances in information technology can be effectively utilized in watershed decision support technology. The Internet-based SDSS provides core functionality required for rangeland watershed management education and decision-making. In comparing digital elevation data of different sources and resolutions with survey data, the DEM data approximated surfaces well, with the higher resolution data producing lower root mean square error values. And finally, different digital elevation models, contributing source area values, and precipitation event sizes produced different management system rankings.

CHAPTER 1

INTRODUCTION

1.1. Problem Overview

Watershed management decision making is inherently complex. It requires cooperation among federal, state, and local stakeholders while incorporating biophysical and socio-economic processes. Traditionally, transfer of information was unidirectional, typically from state or federal government agencies to landowners. In today’s society, bi-directional communication is imperative, expanding the role of land management agencies and the public in the decision-making process. However, federal and state budgets are becoming increasingly constrained and new techniques for information transfer need to be employed. Watershed management decisions are further complicated by both the complexity of the issues and those processes creating the problems. The difficulties in spatially representing and quantifying biophysical and socio-economic processes require that management decisions be based on imperfect information.

As with other disciplines, watershed management in the 21st century is increasingly reliant on information technology (Guertin et al., 2000). Recent advances in data acquisition through remote sensing, data utilization through geographic information systems (GIS), data sharing and communication through the Internet, and the use of models have provided watershed managers with access to more information for making management decisions. Not only is the quantity of data increasing, but the quality of data is also rapidly improving. New technologies, such as interferometric synthetic-aperture radar (IFSAR), are providing data with greater spatial resolution, which increases our capability to analyze and predict water resource phenomena (Wilson et al., 2000). However, the usefulness of this information is often limited because the information is not offered in suitable forms for many decision makers (National Research Council, 1999).

Watershed decision making lies between two conceptual extremes: top-down or bottom-up approaches. The top-down approach for decision making implies that planners, typically from government agencies, prepare a plan and present it to stakeholders. The bottom-up approach involves local stakeholder input from the inception of planning. In a recent national survey, the vast majority (83%) of the public believes they should have more influence on environmental management decisions and trusts the level of government closer to them (i.e. local more than federal) (Steel and Weber, 2001). Involving citizens in the planning process *"insures that good plans remain intact over time, reduces the likelihood of contentious battles before councils and planning commissions, speeds the development process and reduces the cost of good projects, increases the quality of planning, and enhances the general sense of community and trust in government"* (Moore and Davis, 1997).

Effective watershed decision making requires the integration of data, expert judgment, knowledge, and simulation models to solve practical problems and provide a scientific basis for decision making at the watershed scale (National Research Council, 1999). A user-friendly decision support system (DSS) is needed to help various stakeholder groups develop, understand, and evaluate alternative watershed management strategies. The DSS should integrate a set of components consisting of database management systems (DBMS), geographic information systems (GIS), simulation models, decision models, and easy to understand user interfaces that could be available to different stakeholder groups.

An important observation made by the National Research Council's Committee on Watershed Management (1999) is that the difficulty in developing a DSS is not a lack of available simulation models, but rather making these models available to decision makers. Over the last forty years, the federal government has spent millions of dollars on model development. While these simulation models are used extensively in research settings, they are rarely incorporated into the decision-making process. Reasons for this lack of application include: data requirements are usually only attained in a research setting, models are complex and underlying assumptions, limitations, and accuracy are poorly understood by resource managers, deriving model input parameters is extremely time consuming and difficult, and the costs of maintaining and managing the necessary hardware and software systems are high. As hydrologic models continue to be integrated with other technologies, users will be required to have expertise in database management systems, geographic information systems, computer operating systems, remote sensing, and Internet searching for data gathering, as well as watershed domain knowledge. Few seasoned professionals have all these skills, much less the typical watershed stakeholder.

Because successful bottom-up decision making hinges on educating stakeholders, new methods are needed for disseminating applications that provide information to stakeholders. Information technology, in the form of hydrologic simulation models, GIS, and decision support systems, is capable of representing our understanding of the environment, but is often unavailable to stakeholders. The Internet provides a great opportunity for sharing information and applications with decision-makers. However, limitations in availability, architectures, bandwidth, and security present challenges for using this medium. Advances in the communication of information through integrating Internet GIS and simulation models in spatial decision support systems provide opportunities for improving the transfer of information and knowledge from watershed scientists and land managers to decision-makers.

In addition, advances in technology are providing a greater selection of digital data for decision-makers to include in the decision process. These new data can be of similar spatial resolution as existing data, but are derived from different methods for data collection. Since many watershed stakeholders are unfamiliar with these collection methods and therefore cannot evaluate which techniques are better than others, they must rely on scientists and research experiments to determine which data are appropriate for specific tasks.

1.2. Research Objectives

The goal of this research is to develop and evaluate a new methodology to improve information available to watershed management decision-makers. Specific objectives are to analyze rangeland watershed decision-maker’s requirements which include information needed for effective decision-making. Based on these requirements, an application was designed that meets criteria of reusability, availability, scalability, security, and interoperability. The proposed application integrates the latest advances in information technology such as Internet geographic information systems, Web services, relational database management systems, and environmental simulation models within a component based framework.

The specific objectives of this study are:

1. Develop a comprehensive literature review that includes a discussion of applications of spatial decision support systems, and the individual components within spatial decision support technology. The review includes rangeland watershed management, Internet and workstation geographic information systems, hydrologic simulation models, relational database management systems, and Web services.

2. Collect and define requirements for a spatial decision support system that allow watershed managers to easily incorporate hydrologic models into the decision making process. These

requirements allow decision makers to perform simulations, define management alternatives, and consider these alternatives in the analysis.

3. Design and implement an application that performs the procedures and operations defined in objective 2 above. The application and database management system design integrates geographic information systems, Internet, environmental simulation models, and Web services to improve the quantity and quality of information available to rangeland watershed decision makers.

4. Evaluate the impact of digital elevation models and data sources of different resolutions on watershed delineation and hydrologic model parameterization. Digital datasets are constantly evolving and are available from many different agencies. As a result, users have to select the most appropriate DEM for hydrologic analysis.

5. Evaluate the impact of the digital elevation models evaluated in objective 4 on the ranking of

alternative management systems from the spatial decision support system. In addition, the sensitivity of three contributing source area values and six precipitation event sizes on management system rankings by the SDSS will be evaluated.

1.3. Organization of Dissertation

The dissertation is organized into seven chapters with each building on previous sections. The first chapter, Chapter 1, contains background information on watershed management decision-making, highlighting current issues that make this topic of research important. It contains objectives for the dissertation and identifies specific goals that are accomplished through this work. Chapter 2 follows with a review of the literature germane to this research. Chapter 2 includes a discussion of research in the field of decision support sciences including spatial and non-spatial DSSs, components in spatial decision support systems such as graphical user interfaces, geographic information systems, hydrologic simulation models, relational database management systems, and integrating these technologies in different domains.

Chapter 3 describes the design of the spatial decision support system identifying objectives and requirements of the system. The chapter provides an abstract perspective of the SDSS application. Design criteria are described and discussed and the importance of each criterion to the overall spatial decision support system is included. Important design considerations for the spatial decision support system are that it be reusable, extensible, interoperable, accessible, and secure. Use cases describe how users interact with the spatial decision support system which includes a pictorial and procedural perspective of the system.

The discussion on the development of the spatial decision support system is included in Chapter 4. First, a conceptual design is presented including a discussion of the use of Internet geographic information systems, geoprocessing components, simulation models, and a database management system within the design. The implementation of the conceptual design follows, examining the architecture development which includes a discussion of the specific tasks performed by the individual technologies. The implementation is presented within the context of the design criteria presented in Chapter 3, and a discussion of how these design criteria are achieved is included in the chapter.

The readily available digital elevation models used as input for the spatial decision support system are evaluated in Chapter 5. This analysis is performed on the Walnut Gulch Experimental Watershed in southeastern Arizona, where research and data collection has been performed for the past five decades. Six digital elevation models with resolutions ranging from 2.5 to 90 meters created using different technologies are used in this analysis. The DEMs are compared to field survey data to compute and evaluate inherent error in the data. For the different DEMs, watershed and stream networks are delineated and derived parameters from these delineations are compared using different watershed complexities and sizes. The values used for comparison are parameters for hydrologic models and include total watershed area, number of channel segments, mean channel length, mean channel slope, number of upland plane elements, mean upland plane area, and mean upland plane slope.

In Chapter 6, a sensitivity analysis evaluating the impact of the digital elevation models of different sources and resolutions, different contributing source area values, and different precipitation event sizes on the results from the spatial decision support system is performed. Simulations using the six DEMs analyzed in Chapter 5 are conducted on six management systems to determine if the different DEMs change the ranking of the management systems. In addition, management system rankings are compared using three contributing source area values (1.5, 8.0, and 15 percent) and six precipitation event sizes (5 year 30 minute, 5 year 60 minute, 10 year 30 minute, 10 year 60 minute, 100 year 30 minute, 100 year 60 minute). Management systems are ranked based on minimizing sediment yield where higher ranked management systems produce lower simulated sediment yield values.

The summary and conclusions are presented in Chapter 7 followed by the Appendix and list of literature cited. The Appendix contains definition of terminology, screen captures of the application, an overview of the hydrologic model used in the SDSS, a data dictionary for the SDSS database, Unified Modeling Language sequence diagrams, methodology for simulation range management practices within the SDSS, and Chapter 5 and 6 simulation results.

CHAPTER 2

REVIEW OF RELEVANT LITERATURE

2.1. Introduction

This chapter reviews relevant literature for this research on the design, development, implementation, and testing of the spatial decision support system for rangeland watershed management. It begins with a discussion on research in the field of decision support sciences. Topics include the development of spatial and non-spatial decision support systems for different domains and reasons for poor adoption and success rates. A discussion of the components in spatial decision support systems follows including graphical user interfaces, geographic information systems, hydrologic simulation models, relational database management systems, and the integration of these technologies. The literature review concludes with a summary and discussion on why this research is relevant.

2.2. Spatial Decision Support Systems

2.2.1. Overview

Spatial Decision Support Systems (SDSS) are developed to integrate data, knowledge, and modeling results to identify, evaluate, and recommend alternative solutions to spatially distributed problems (Djokic, 1996; Bellamy et al., 1996; Prato and Hajkowicz, 1999). Decision support systems have progressed from tools that simply provide users with the resources to formulate, assess, and compare alternative solutions to applications that educate users about the problem context and how the problem has come into existence (Bellamy et al., 1996). With education as the primary focus, managers and planners can more easily adapt to changing situations through understanding of the causal relationships of the situation at hand (Climaco et al., 1995; Bellamy et al., 1996).

In natural resource management, Decision Support Systems (DSS) have been successfully developed for complex problems, and in many cases these systems have reached or exceeded the level or performance of recognized human experts (Coulson et al., 1987). For example, a DSS was developed for Australian rangelands to assess the sustainability of grazing management systems (Bellamy et al., 1996; Bellamy and Lowes, 1999). Specifically, this system assessed the spatial variability of the vegetation condition and soil erosion risks for grazing management units, formulated alternative scenarios and assessed the impacts of these scenarios on vegetation condition and soil erosion risk, and evaluated the implications for pasture and cattle production and the profitability for each scenario (Bellamy and Lowes, 1999). A DSS used to evaluate the impact of alternative agricultural management systems on surface and groundwater quality and farm income was developed by the USDA ARS Southwest Watershed Research Center in Tucson, AZ (Yakowitz, et al., 1992; Yakowitz et al., 1993; Heilman et al., 1994; Heilman et al., 1997). Spatial decision support systems have also been developed to assess sustainability of resource management at the field and watershed scales (Pereira and Duckstein, 1993; Prato and Hajkowicz, 1999; Joerin and Musy, 2000).

The adoption and success rates of decision support systems and spatial decision support systems have been relatively low despite the effort, time, and money spent on developing these applications (Uran and Janssen, 2003). Newman et al. (2000) attributed this lack of adoption to the complexity and quantity of data inputs, limited computer ownership, and a lack of understanding by potential users of the underlying theories of included models (Newman et al., 2000). After examining five spatial decision support systems for coastal zone and water management, Uran and Janssen (2003) concluded that difficulties in specifying alternatives, complexity in navigation resulting from a large number of options, and lack of adequate support to the decision process are major reasons for the low adoption rates. Furthermore, they stated that a closer link between developers and users during development would potentially lead to higher adoption rates in the future.

2.2.2. SDSS: Components

Spatial Decision Support Systems are created either from the ground up, writing the entire program from scratch, or by linking existing application that provide the necessary tools (Djokic, 1996). Since writing the application from scratch is complex and reinvents procedures to provide required functionality, SDSS shells are usually created by linking existing applications (Djokic, 1996). Spatial Decision Support Systems typically include remote sensing, geographic information systems, analytical models, a user interface, database management system, and knowledge based system (Sugumaran, 2002; Densham, 1991; Fedra, 1991). In the watershed sciences, the linkage is commonly made between hydrologic/water quality simulation models, a GIS, and a relational database management system which provides an efficient means to store, analyze, and visualize results from the model (Yoon, 1996). Djokic (1996) points out that a burden with linking existing applications is that interfaces must be created for individual software components to allow data transfer and command control. However, recent advances in information technology allow GIS software and commercially available RDBMS to be compatible, which provides an opportunity for a seamless integration between database management systems and geographic information systems.

§ ***User Interface***

Decision support system research has historically focused on data, procedures, rule sets, text, forms, and spreadsheets associated with the problem decision area (Sankar et al., 1995). However, the user interface has been deemed to be the most important aspect (Sprague and Carlson, 1982) and acceptance of decision support systems is largely dependent on their ease of use (Uran and Jassen, 2003), which is often controlled by the user interface. The user interface coordinates the communication between the user and the application. A good dialog should be error tolerant and provide user help as carefully phrased informative messages (Molich and Nielsen, 1990). The user interface should be easy to learn, allow graceful shifting from one task to the next, provide a high level of guidance and feedback based on a user’s interactions while giving the user the sense of being in control (Holsapple and Whinston, 2001).

§ ***Geographic Information Systems***

Geographic Information Systems are at the core of Spatial Decision Support Systems. GIS can incorporate data addressing multi-ownership, infrastructure, and economic concerns. GIS offers the capability to explicitly model the spatial heterogeneity in landscapes, pasture utilization, and distribution of management units (Bellamy et al., 1996; Bellamy and Lowes, 1999) and effectively analyze non-point source pollution problems (Fraser et al., 1996; Yoon, 1996; Fraser et al., 1998; Guertin et al., 1998; Basnyat et al., 2000). Management tools, such as Spatial Decision Support Systems, are more effective if they are user friendly and easily accessible. The Internet provides a convenient forum for technology transfer (Lane et al., 1999); however, applications utilizing spatial technologies available through the Internet have costly performance considerations.

The Internet has existed for over 30 years but only recently have Geographic Information Systems utilized Internet technology, which has the potential for exponential increases in the efficiency and effectiveness of the ways in which we obtain, share, and process geographic data (Plew, 1997). The web utilizes a client-server architecture that allows data storage, extraction, and processing functions computed on a remote server, while visualization functions are performed at the local client through a web-browser (Abel et al., 1998). Some of the current applications of Internet-GIS include UCLA’s GIS Database and Map Server (http://gisdb.cluster.ucla.edu), National Geographic’s Interactive Atlas (http://www.nationalgeographic.com/mapmachine), Federal Emergency Management Agency’s (FEMA) hazard maps (http://www.esri.com/hazards/index.html.), and a visualization tool (GEO-VRML) developed in cooperation with the EPA (http://www.epa.gov/gisvis/index.html).

The Internet-GIS architecture determines the complexity and efficiency provided by the application. The simplest architecture is a thin client architecture, where the application runs in a standard web browser (i.e. Microsoft’s Internet Explorer or Netscape’s Navigator) and requires little processing power for the user (Abel et al., 1998). Using this type of architecture, spatial data are transferred as image files in a format compatible with available web browsers. More complex applications require a “thicker” client consisting of either a browser plug-ins or an applet. A plug-in is an independent software component installed locally that is automatically started when data of the specified type is received. An applet is a platform independent, Java program that is transmitted with the data and has the potential to bridge the gap between web GISs and non-web GISs (Wang and Jusoh, 1999). Both approaches provide for developmental capabilities suitable for diverse spatial data applications (Abel et al., 1998).

Many applications have been created using different architectures. Abel et al. (1998) developed two applications of different complexities and discuss the access time through the Internet. The first application provided Internet access to Australia’s government cadastral and related databases. In this application, the client was only required to zoom, pan, and request additional information about the data. This application was simulated using a Java applet that performed “very similar to that of a conventional GIS” (Abel et al., 1998). The second application was more complex, producing maps from vector and raster data linked to a temporal aspatial database. This application contains two Applets, one for viewing spatial data and the other is an independent graph viewer. When the user pans to the map view, the raster data were required to be re-transmitted, delaying the viewing application (Abel et al., 1998). However, changes in design of the internet-GIS architecture can limit the number of times the client contacts the server thus decreasing potential delays. Other applications using Internet GIS include web-based mapping for urban systems (Doyle et al., 1998), a web-based application for visualizing GIS data (Huang and Lin, 1999), and an internet-based GIS application for an investment environment (Lin and Zhang, 1998). Research has also been conducted on the development of a 3-dimensional GIS deployed through the Internet (Lee et al., 1998) and integrating multiple internet-based geographic information’s systems into one system (Wang and Jusoh, 1999).

§ *Hydrologic Simulation Models*

Originating in the latter half of the 19th century, hydrologic models have long been used in watershed management. They provide an important resource for evaluating and assessing hydrologic systems, and managers are increasingly reliant on this technology to support decision making. The classification, application, and development of available models has been reviewed in great detail by others (see Singh, 1995; Maidment, 1993 for synopses). The majority of models applied today perform simulations using methods derived in the early 20th century. When these methods are implemented with today’s technology, it raises questions regarding the applicability of these tools. For example, Green-Ampt’s infiltration equation was developed as a point model to estimate infiltration under saturated conditions, and is now commonly applied over large landscapes using distributed hydrologic simulation models. However, physically-based, spatially distributed infiltration equations have not been developed, so this is the best approach available. Even though the first watershed-scale, computer based simulation model was developed almost forty years ago in the Stanford Watershed Model (Crawford and Linsley, 1966), simulating watershed-scale processes continues to be an extremely challenging activity, in spite of recent advances in data quantity and quality, and technologies to manage the spatial attributes of watersheds. The National Research Council (1999) recommends that tools be developed to facilitate the transfer of simulation modeling technology, which will provide modeling results to managers for decision making, “even if they are based on imperfect information.”

A recent trend in hydrologic modeling is to utilize geographic information systems to develop parameter sets and visualize simulation results. Four approaches exist for integrating models and GIS: embedding GIS in the hydrologic model and vice versa, and loose and tight coupling between the components (Sui and Maggio, 1999), with each approach having advantages and disadvantages. Embedding the GIS functionality in the hydrologic model provides the most flexibility for application design, eliminating dependencies on previous GIS data structures, but most hydrologic modeling packages do not provide the visualization capabilities of commercial geographic information systems (Sui and Maggio, 1999). Embedding hydrologic modeling functionality in GIS has recently been conducted by vendors such as ESRI and Intergraph, but the modeling capabilities are usually simplistic and calibration and verification must be conducted outside the GIS (Sui and Maggio, 1999). Loose coupling is completed using “stand alone” GISs and hydrologic models that exchange data using an ASCII or binary data format. Loose coupling relies on existing components, therefore reducing the programming required to develop these technologies, but data conversion between the components can be tedious (Sui and Maggio, 1999). The final approach, tight coupling embeds a hydrologic model within a commercial GIS utilizing the application’s capability to be customized using scripting languages such as ESRI Avenue or AML (Sui and Maggio, 1999).

These four integration approaches have yielded numerous applications that utilize a combination of loose or tight coupling methods (Sui and Maggio, 1999). The Automated Geospatial Watershed Assessment Tool (AGWA; Miller et al., 2002) uses a hybrid between the loose and tight coupling where specialized routines are created using

ESRI’s Avenue programming language to prepare input files, but the communication between the GIS and hydrologic models are performed using an ASCII text format. A similar approach was used in developing a generic object-oriented modeling framework (McKinney and Cai, 2002) and integrating GIS into Agricultural Nonpoint Source Pollution Model (AGNPS: He, 2003; He et al., 2001), Better Assessment Science Integrating Point and Nonpoint Sources (BASINS: Lahlou et al., 1998), Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS: De Roo et al., 1989), and the Soil and Water Assessment Tool (SWAT: Srinivasan and Arnold, 1994). The US Army Corps of Engineers also used a loosely coupled approach integrating GIS and their Hydrologic Engineering Center River Analysis System (HEC-GeoRAS: Ackerman, 2002).

Recently, a number of Internet-based hydrologic applications have been realized. These applications offer several advantages over traditional stand-alone computer applications. A typical Internet application offers a centralized simulation model that does not require installation on local computers and provides access to the latest version of the software at all times. Internet applications do not require advanced software or hardware for the end user, since these applications operate through a web browser, with most of the processing conducted on the server. However, deploying applications over the Internet alienates user groups since access to the Internet is not ubiquitous.

Two examples of currently developed, web-based hydrologic and erosion applications are: 1.) the work of Dr. Leonard Lane and other scientists at the USDA-ARS Southwest Watershed Research Center in Tucson, AZ and 2.) the effort of scientists at the USDA-FS Rocky Mountain Research Station in Moscow, ID. The Southwest Watershed Research Center developed an Internet-based Hillslope Erosion and Sediment Yield Model (HEM: http://eisnr.tucson.ars.ag.gov/hillslopeerosionmodel). The model predicts runoff volume, sediment yield, interrill and rill detachment, rill deposition, and mean concentration of sediment for hillslope segments. The model estimates output using hillslope segment lengths, slopes, percent canopy and surface ground cover for each hillslope segment along with runoff volume and a soil erodibility value for the entire hillslope. The HEM model produces graphs depicting the input hillslope profile and distribution of cover on the hillslope and output for sediment discharge, detachment and deposition, and mean sediment concentration along the hillslope profile.

The Rocky Mountain Research Station developed the Forest Service Water Erosion Prediction Project (FSWEPP) interfaces, which provide the capability to evaluate erosion and sediment delivery from forest roads. The application uses the Water Erosion Prediction Project (WEPP) model (Lane et al., 1992) to estimate erosion rates and sediment delivered using input values developed at the Rocky Mountain Research Station (Elliot et al., 1999). The interface provides links to models capable of simulating sediment yield from a road segment across a buffer, and soil erosion from forest roads, rangeland, forestland, and forest skid trails.

Both the HEM and FSWEPP applications perform simulations at the hillslope scale and can incorporate field observations. They do not provide the capability to estimate the cumulative response for several adjacent hillslopes nor address watershed scale responses. Most watershed problems must be addressed at the watershed scale, and therefore, require the application of a watershed scale model. This increases the complexity required of Internet applications. Users must be provided with the capability to identify and delineate watersheds using site specific data and to summarize watershed characteristics for specific model applications.

§ *Relational Database Management Systems*

With respect to watershed management, relational database management systems research has focused on data model development. Maidment (2002) created a generic water resource data model that combines geospatial and temporal data to support hydrologic analysis and modeling. This ArcHydro approach provides a data modeling framework that includes hydrologic networks, drainage systems, river channels, hydrography, and time series data. In addition, ArcHydro provides implementation details for the data model.

2.2.3. Component Integration

Two object-oriented model integration efforts have been conducted by the USGS in developing the Multi Modeling System (MMS: UC Boulder, 1993) and the USDA ARS in developing the Object Modeling System (OMS: David, 1997). Both architectures represent physical processes as objects as an attempt to improve interoperability between modeling components. Both systems provide objects that use different methods for simulating fundamental hydrologic processes such as infiltration, overland flow, channel, and routing. This framework allows users to create custom simulation models that could combine the KINEROS channel routing object, the Hydrologic Simulation Program – Fortran (HSPF) infiltration object, the WEPP erosion object, and so forth. The MMS modeling framework operates in a Unix environment which has slowed its adoption. OMS utilizes Java and XML technologies providing an operating system independent framework. Both efforts have been faced with challenges resulting from the incompatibility of assumptions and time steps among the different modeling objects.

2.3. Summary

These separate advances in Internet and desktop geographic information systems domains, combined with research on integrating hydrologic modeling and GIS and deploying hydrologic models via the Internet, make designing and developing an integrated spatial decision support system for rangeland watershed management possible. This research leverages recent advances in technologies to overcome identified causes for the lack of adoption of decision support systems by Newman et al. (2000) and Uran and Janssen (2003). Utilizing the power of geographic information systems to minimize data required by users and the Internet to make the application accessible makes this application unique and current. In addition, integrating object-oriented design principles and geoprocessing, and hydrologic modeling Web services into the spatial decision support system provides a flexible, modular design capable of being expanded to incorporate additional environmental concerns and new simulation models.

CHAPTER 3

REQUIREMENTS OF THE SPATIAL DECISION SUPPORT SYSTEM FOR RANGELAND WATERSHED MANAGEMENT

3.1. Introduction

This chapter describes the user requirements, application functionality, and design objectives for the spatial decision support system for rangeland watershed management. It provides a framework for which the SDSS design will be evaluated and describes functionality required of the application. Specifically, a general discussion of the key functionality that the spatial decision support system must include is presented followed by more specific use cases and use case pathways. In addition, design criteria are presented to identify how the spatial decision support system can be expanded to include additional hydrologic simulation models, accessible to different user groups, interoperable so that components can be used by other systems, and secure protecting user’s sensitive information (See Appendix A for glossary of terms).

3.2. Rangeland Watershed Management

In semi-arid watersheds, control of erosion on uplands to reduce sediment delivery to channels greatly affects downstream water supplies along with sustained capability of rangelands to produce forage (Renard, 1970). As a result, an important objective of rangeland watershed management in the semi-arid southwest is to design and implement management plans that minimize costs, and have the lowest erosion and sediment yield from a defined area (i.e. a watershed). Management practices available to rangeland watershed managers when designing management systems include the location and size of pastures, location and quantity of water points within a pasture, hydraulic structures such as detention ponds to capture runoff and sediment, critical area planting, adjusting stocking rates, grazing systems, season of use and duration (Holecheck et al., 1995). Each of these management practices has an associated economic cost and an environmental effect. As more management practices are combined into management systems, the accumulated cost and effect becomes difficult to quantify and compare with other systems.

The scale at which the management decisions are made and spatial issues related to ranch and watershed boundaries complicate watershed management decisions. A watershed may contain multiple management system structures such as a pasture, or a management system structure may span multiple watersheds. Moreover, a watershed may be comprised of multiple landowners, each with different management objectives. As an example, the Walnut Gulch Experimental Watershed contains land parcels owned by private, state, and federal organizations. Because land use location within a watershed is extremely important in determining the hydrologic response, watershed management decision must be based on both what and where practices are implemented.

The proposed spatial decision support system will assist rangeland watershed managers evaluate management systems that include the properties and location of recognized management practices. Since there are numerous

Best Management Practices (BMPs) to choose from and a number of hydrologic models to perform the simulations, the design must be flexible to accommodate new BMPs and simulation models.

3.3. User Requirements

The user requirements were gathered based on examining the literature, the watershed decision-making process, and evaluating the capabilities of other watershed-based applications. Discussions with watershed management experts at the University of Arizona and USDA-ARS Southwest Watershed Research Center in Tucson also provided insight into how this application should function and what it should accomplish. Based on these inputs, the following key requirements were identified.

§ ***Interactive view of spatial data***

Users of the spatial decision support system require extensive interaction with spatial data through a web browser. The required navigation include operations such as pan in the four cardinal directions, zoom in and out, toggle spatial layers on and off, and change the order of layers. This provides users with the basic functionality found in desktop geographic information systems software via the Internet.

§ ***Delineate watersheds***

Watershed managers will need to delineate watersheds of concern through the user interface. The process should be performed by locating an outlet on a map or aerial photograph, and having the application determine the watershed boundary from the user specified outlet location. To simplify locating the outlet location, the user will select the watershed delineation tool and “click” on the map to locate the outlet point. Once the watershed boundary is delineated, the boundary, along with a generalized stream channel map, should be dynamically added to the map for the user to view.

§ ***Parameterize simulation models***

Users will need to parameterize simulation models for a given watershed boundary while providing minimal data as input. Users will need to perform three types of parameterizations: topographic, soils, and land cover. Topographic parameterization requires the watershed boundary and stream network to be subdivided or discretized into modeling elements with topographic dependent model parameters (i.e. slope) calculated for each element. The soils parameterization will need to calculate soil dependent model parameters based on user selected digital soils data. Similarly, the land cover parameterization will need to calculate model specific land cover parameters based on user selected digital land cover data.

§ ***Perform simulations on watersheds***

Users will need to perform simulations using the parameterized watersheds and view results. The simulations will be performed using user selected watershed and storm events.

§ ***Visualization***

The results will be viewed spatially through the web interface. Users will need to visualize areas within a watershed that produce higher rates of runoff and erosion.

§ ***Define rangeland watershed management systems***

Users of the spatial decision support system will need to define rangeland watershed management systems that include appropriate management practices for semi-arid environments. Users will define management systems by selecting the desired practice and locating the practice on the map. Users must be able to provide attributes of the practice that are stored by the application. Users should be able to add multiple practices to a management system, move the location of a previously added practice, or delete a management practice from a system.

§ ***Perform simulations incorporating user defined management systems***

Users must be capable of performing hydrologic simulations including their management systems in the analysis. The application will adjust the appropriate model parameters based on the user defined management system and conduct the simulation. Users must also be capable of viewing the results of simulations in spatial, graphical, and tabular formats.

§ ***Compare simulation results of alternative management systems***

Users must be capable of viewing results from management system alternatives. Results should be presented in tabular format including the management system name, simulated values for runoff and sediment yield, and an estimate of the cost of the management system.

3.4. User Interaction

The primary function of the internet-based SDSS application is to allow the user to perform simulations and design management practices for a given sub-watershed / ranch land unit. The interaction of the user with the application will typically begin at the SDSS home page and terminate with the management simulation results. The specific user interactions accounted for in the application are:

1. The user connects to the application by directing a browser to the URL of the application's homepage. The user can browse information about the project, resources on management practices, or a tutorial of the project.
2. At any point of the interaction, the user can sign-in to their account or create a new account. The user is required to set-up an account to save data to the database.
    i. If the user has an account, they can login using a secure connection and have access to spatial data, simulation results, and other information created during a previous interaction. The user can either

start at the beginning of the application, or if the user stopped a previous interaction before the application was completed, the user will have the option to continue the application from the previous session.

ii. If the user is not currently a subscriber, they can provide basic user identification information and an account will be created with the given user name/password. The application will send the user a welcoming email notifying them of their new subscription and provide basic information about the application.

3. The user can browse through spatial data of map layers for a given region, currently southwestern Arizona, which will include hydrography, Digital Ortho Quarter Quads (DOQQ), Digital Elevation Models, Digital Line Graph (DLG), soils data, land cover data, and Census 2000 data along with current water bodies on the EPA’s 303d list with the constituent for which the water body is impaired. This information will be available to all users while user-specific information (entered through interaction 4) will only be available to the given user.

4. The user can locate their area of interest by using map layers containing regional and local benchmarks. Once the user identifies their area of interest, they can click on the map to delineate a watershed boundary that is dynamically added to the map.
5. The user can perform a simulation using the boundary by selecting the simulation tool and clicking on the boundary.
6. The user has a list of model parameter sets available for a simulation or can create new parameter sets by selecting on the land cover or soils digital dataset. Once the user selects a combination of a soil and a land cover parameter set, they can perform a simulation. Results from the simulation are spatially displayed on a map and the user is provided with the option of viewing different output values from the model.
7. After the user has performed a simulation, they have two options to enter ranch infrastructure information:
    i. The user can create GIS features via heads-up digitizing of their ranch infrastructure. Pre-defined feature type objects will be available for the user to choose from (such as fence lines, water sources, etc.) and will contain attributes necessary

for model simulations. For example, the user could select the “fence” feature type and then draw a polygon to locate the position of the fence. Specific attributes of the fenced area (pasture) will be entered for the simulations, and the view will be updated with pre-defined symbols. This information will be transferred to persistent storage for later interactions.

ii. The user can upload existing ranch infrastructure data from existing databases on local machines. The application will have to account for possible projection and attribute differences and correct the problems.

8. When a management system is completed, the user submits the management system. Model parameters are adjusted based on the location and attributes of the management system, and results are returned to the user in a graphical, tabular, and spatial format.
9. The previous step can be repeated multiple times allowing users to compare the predicted outcomes of different management systems on producing runoff and sediment.

10. Finally, the user can logout of the application and the current status of the interaction will be saved for the next interaction.

This is a typical user interaction with the fully functional SDSS application. The application will include additional functionality such as a spatial query module that will assist the user in identifying locations of interest for their simulation. Locations can be queried by city, street intersections, or parcel id. While the interaction presented above is from a single user's point of view, the application will be capable of supporting multiple interactions simultaneously.

3.5. Use Cases

Use cases capture the core behavior of an application without specifying how the behavior is implemented (Booch et al., 1999). Eleven use cases are identified that are required for the SDSS to facilitate the decision process (Figure 3.1).

Case 1: Create Account – The user creates a new account by providing a username, password, and contact information.

Case 2: Login – The user provides a username and password and if authenticated, he/she is provided access to their data.

Case 3: Alter Map – The users selects a map operation tool and clicks on the map. A new map is displayed based on the operation performed by the user.

Case 4: Delineate Watershed – The user locates a watershed outlet by clicking on a map. From the user entered location, a watershed boundary is created and added to the map.

Case 5: Topographic Model Parameterization – The users selects the boundary for which the topographic parameterization will be performed. The watershed boundary is subdivided into modeling elements and model specific parameter values are estimated based on the digital elevation model used in the analysis.

Case 6: Soil Model Parameterization – For a given topographic parameterization, the user selects the digital soils layer and the model parameterization is performed.

Case 7: Land Cover Model Parameterization – For a given topographic parameterization, the user selects the digital land cover layer and the model parameterization is performed.

Case 8: Perform Hydrologic Simulation – The user selects the soils parameter set, the land cover parameter set, and the precipitation event and a model simulation is performed. The results from the simulation are displayed spatially and different output values can be selected by the users for display.

Case 9: Create Management System – The user selects the management practice they want to include in the management system. The user then locates the system by “pointing” and “clicking” on the map. The user also has the option to attribute the management practice, and move or delete the practice.

Case 10: Perform Management Simulation – For the current management system, the user performs a new simulation to estimate the runoff and sediment yield. Intermediate models and subroutines are utilized to estimate livestock distribution provided the type and location of management practice (i.e. pasture boundaries and water points). Hydrologic simulation model parameter values are adjusted and simulations are performed.

Case 11: View Results – Once users have completed a simulation that includes user defined management systems, the user can view the results. Results are presented in a graphical, tabular, and spatial format.

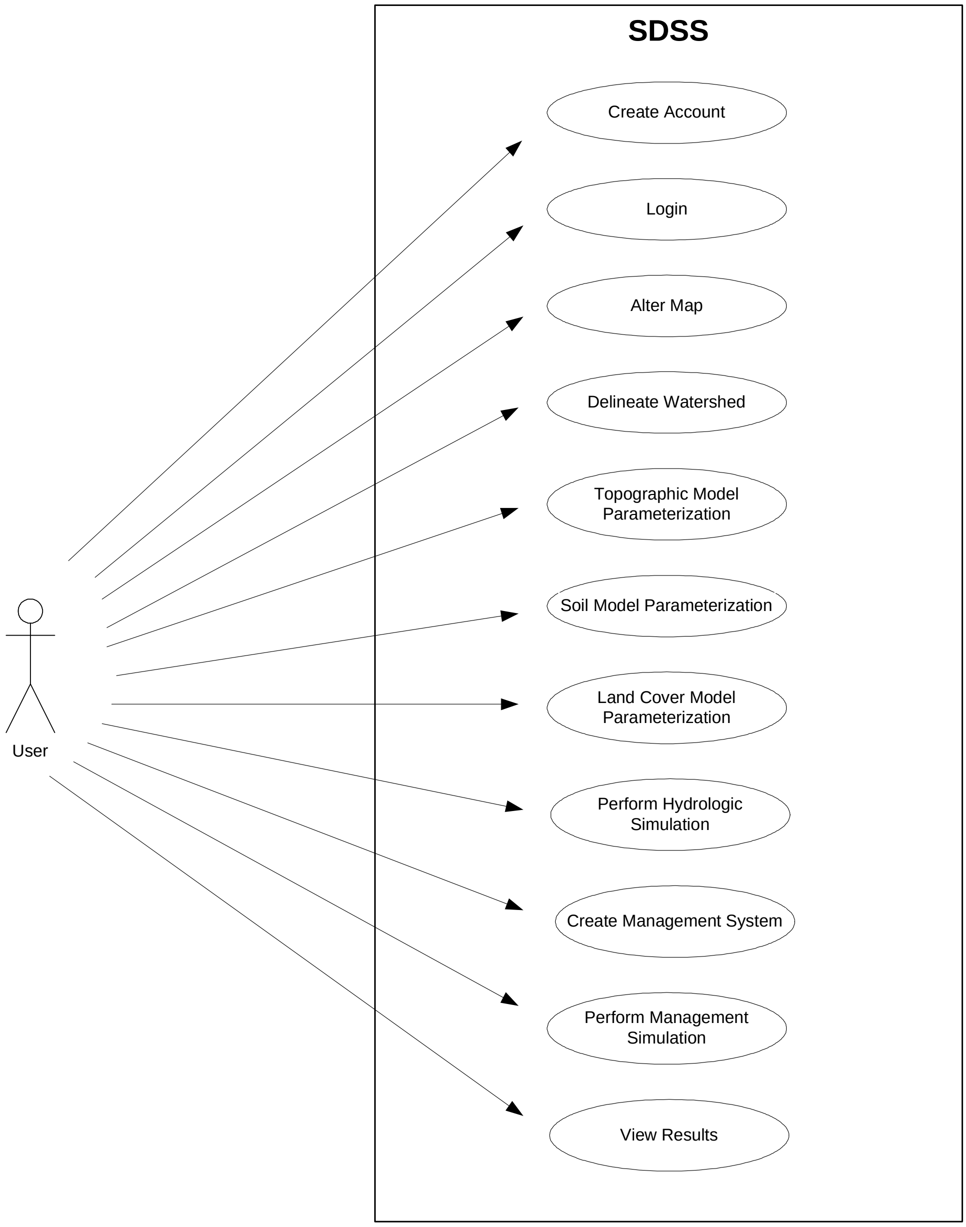


Figure 3.1 Use Cases for the Spatial Decision Support System for rangeland watershed management

3.6. Use Case Pathways

While Use Cases provide the overall functionality of the spatial decision support system, Use Case Pathways illustrate a finer grained, procedural perspective for how the Use Cases are accomplished. Use Case Pathways highlight the individual steps required to implement a Use Case.

Case 1: Create Account

a) User sends account information
b) System verifies that the username is unique
c) System loads user data into the database
d) System generates session requirements for the user

Case 2: Login

a) User posts username and password
b) System verifies user information
c) If successful, system generates session requirements for the user

Case 3: Alter Map

a) User sends requests that will be performed on a map
b) System performs the action(s) received
c) System generates new map
d) System returns location of map to user

Case 4: Delineate Watershed

a) User sends the coordinates of the watershed outlet
b) System delineates the watershed based on the outlet location
c) If the user is signed in, system stores watershed boundary in the database
d) System calls Alter Map Use Case adding the delineated watershed to the map
e) System generates a new map
f) System returns the location of map to user

Case 5: Topographic Model Parameterization

a) User selects the watershed boundary and the model to perform the topographic parameterization
b) System performs the topographic parameterization

c) If the user is signed in, the system adds the results to the map using the Alter Map Use Case

d) System generates a new map

e) System returns the map location to the user

Case 6: Soils Model Parameterization

a) User selects the topographic parameter set, soils coverage, and look-up table to perform soils parameterization

b) System performs the soils parameterization

c) If the user is signed in, the system stores the results in the database

Case 7: Land Cover Model Parameterization

a) User selects the topographic parameter set, land cover grid, and look-up table to perform land cover parameterization

b) System performs the land cover parameterization

c) If the user is signed in, the system stores the results in the database

Case 8: Perform Hydrologic Simulation

a) User selects the topographic parameter set, land cover parameter set, soils parameter set
b) System generates the parameter file(s)
c) System generates the precipitation file
d) System performs the model simulation sending the input files to the hydrologic simulation model
e) System adds the results for each element to the map using the Alter Map use case
f) System generates a new map
g) System creates a graph for the time series results
h) System returns map and graph to the user

Case 9: Create Management System

a) User delineates the management system on the screen using digitizing tools provided by the system
b) User sends management system to the application
c) System stores the management system in the database

Case 10: Perform Management Simulation

a) User sends the management system that will be used in the simulation
b) System modifies the base management simulation
c) System generates the parameter file containing the management adjusted parameters
d) System generates the precipitation file
e) System performs the simulation sending the input files to the hydrologic simulation model
f) System adds the results for each element to the map using the Alter Map use case
g) System generates a new map
h) System creates a new graph adding the new time series results to existing simulation results
i) System returns map and graph to the user

Case 11: View Results

a) User selects the format for results display. User has the option to view results in a tabular, graphical, or spatial format.
b) User selected format is displayed for the user

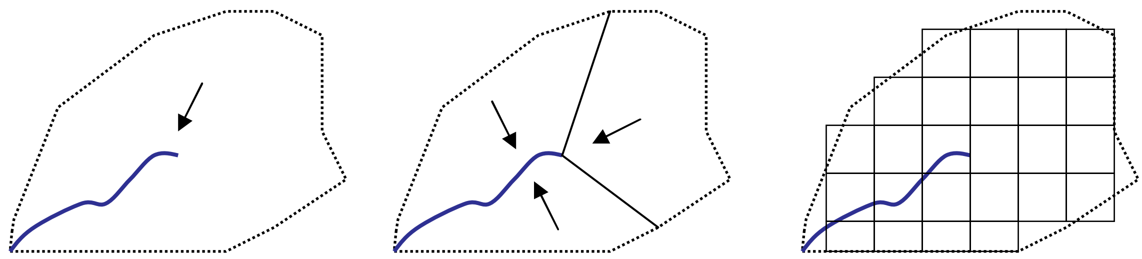
3.7. Additional Design Considerations

In addition to the user requirements identified above, the spatial decision support system will need to meet certain design criteria to ensure it to be adopted by users and expanded with new features. Specifically, the SDSS will need to be extensible so that new simulation models and management practices can be added in the future, accessible so that users have the opportunity to use the application, interoperable so that existing components can be incorporated into other applications, and secure so that users are comfortable storing data in the application. These criteria are discussed in greater detail below.

3.7.1. Extensible

The use of physically based hydrologic technology is domain, spatial, and temporal specific since hydrologic simulation models are developed to address certain environmental problems and models simulate the dominant hydrologic processes. These models contain complex equations that are abstractions of reality. As a result, models developed for certain geographic regions are not applicable to other geographic regions. For example, the dominant runoff generating mechanism in the semi-arid southwest is Hortonian overland flow and since hydrologic flow paths such as interflow are negligible, models developed for this region often ignore this component. However, in regions such as the forested Pacific Northwest, surface runoff is often insignificant as interflow is the dominant runoff generating flow path. Temporal considerations such as spring snowmelt or summer convective thunderstorms need to be included in the simulated processes. Moreover, since simulation models contain different hydrologic process representation, the parameters required by models also differ.

In addition to the differences in process description between models, the ontological representation of watersheds in simulations models also differs. As a watershed is divided into hydrologically homogenous units, the representation of the area by hydrologic simulation models differs. Common model discretization schemas include the single upland element (Figure 3.2a) where each channel element has only one contributing upland element, the “open-book” representation (Figure 3.2b) where each channel element has two lateral upland elements with each upland element contributing to either sides of the channel, and a grid representation (Figure 3.2c) where watersheds are subdivided into uniform pixels with each pixel representing a hydrologically homogenous unit.



a b c

Figure 3.2. Different watershed representations in hydrologic simulation models. (a) a single contributing element to stream channel, (b) open book configuration where multiple upland elements contribute to a stream channel, and (c) grid representation where watershed is subdivided into grid cells.

Hydrologic models have different temporal representations for which processes are simulated and are classified as either continuous-time models or event-based models (Singh, 1995). Event based models perform simulations for single precipitation storms where processes are often simulated on hourly or smaller time steps. These models include processes to estimate the hydrologic response given a single rainfall event. Therefore, antecedent conditions such as soil moisture are required as input parameters to the model. Continuous hydrologic models simulate processes from several years to decades, frequently at daily or longer time steps. These models must include processes to simulate changes in soil moisture and differences in evapotranspiration rates through the year.

Because hydrologic models differ in their processes simulated, parameter requirements, watershed representation, and temporal representation, the spatial decision support system must be extensible providing the capability to include new models with little modification. Extensible is defined as a system that can be modified by changing or adding features. In making the SDSS extensible, new models that potentially address different environmental issues (threatened and endangered species, for example), and spatial and temporal resolutions could be easily included in the decision support system.

3.7.2. Interoperable

Because watershed management decision making requires a coordinated effort between stakeholders representing different groups and levels of government, integrated decision support systems should facilitate interaction and communication among agencies' information systems to make the group decision-making process more efficient. However, different competing application programming platforms (i.e. Java, Visual Basic, FORTRAN, etc.), operating systems (i.e. Window, Unix, Linux, etc.), and database management systems (i.e. Oracle 9i, MS SQL Server, MySQL, etc.) make communication difficult or impossible. Standardizing programming languages, operating systems, and database management systems for watershed management stakeholders is impractical because different groups have distinct budgets, legacy systems, and requirements for their IT infrastructure. Creating a centralized database repository containing watershed management data for decision making is a possibility, but leads to logistical issues such as what data should be contained in the database, who administers the database, how often is the database updated, and who pays for infrastructure. Component based frameworks have been adopted such as Microsoft's Component Object Model (COM), but lack the inclusion of all programming languages and all operating systems. A standardized interface that is both programming language and platform independent should be utilized when developing integrated watershed decision support systems because it allows the different management IT systems to interoperate.

Years of research and development have been spent on developing simulation models that encapsulate our understanding of environmental processes. These applications represent the current state of knowledge and should be leveraged in the decision-making process. However, these models are often developed using technologies which make interaction with today's object-oriented, web-based technologies cumbersome or impossible. Because different programming languages are developed for different purposes, languages that are computationally efficient are often not compatible with languages that have extensive libraries for Internet development, and no single language is ideal for all applications. Therefore, an integrated decision support system must be capable of incorporating legacy applications that are built with technologies that do not communicate with Internet capable programming languages.

The Spatial Decision Support System must be designed and implemented using interoperable components that can be utilized by other applications and/or other resource agencies. The objective is to create components that can be integrated into new applications independent of location, programming languages, operating systems, and database management systems. Achieving this objective provides the flexibility and independence from commercial off-the-shelf (COTS) GIS environments such as ESRI ArcView 3.X (ESRI, 1998) where traditionally, applications had to be rewritten as COTS desktop environment changed. As used in this context, interoperability is the ability for systems or software components of a system to operate reciprocally, overcoming barriers imposed by heterogeneous processing environments and heterogeneous data (Buehler and Mckee, 1998).

3.7.3. Accessible

Traditional decision support systems were developed as single computer applications such as DOS or UNIX based systems in the 1970s and Windows in the 1990s (Shim et al., 2002). These workstation-based applications present challenges for users who are required to maintain applications which is a daunting task for many non-technical land managers. Moreover, since the spatial software incorporated into spatial decision support systems is often proprietary, the cost and expertise required to operate these applications exceeds that of the majority of rangeland management stakeholders. Therefore, the proposed application must be made available to stakeholders who do not have access to COTS GIS software or extensive computer experience.

3.7.4. Secure

Security is always a concern in Internet environments and reports on security breaches in Internet environments are frequently documented (Palmer and Helen, 2001). If web-based applications are going to be integrated into the decision-making process, precautions need to taken to assure application security. The SDSS will contain data that users may consider “sensitive”, such as management activities on private lands. Secure applications can lead to users trusting the design and architecture of the application; conversely, users are unwilling to expose themselves to unnecessary risks. The proposed application must provide a secure environment to store user specific data.

CHAPTER 4

DEVELOPMENT OF A PROTOTYPE SPATIAL DECISION SUPPORT SYSTEM

4.1. Introduction

Chapter 4 describes the design and development of the Spatial Decision Support System. The application design follows from the design objectives, functionality, and requirements described in Chapter 3. This chapter first presents the conceptual design and includes a discussion of the individual components of the SDSS; specifically, the components include Internet Geographic Information Systems, geoprocessing components, a Database Management System storing both spatial and aspatial data, and simulation models. Following a discussion of the individual components, the implementation of these components integrated into one system is illustrated. Finally, the implementation of the design is evaluated based on the design objectives presented in Chapter 3 and the benefits of the SDSS architecture are discussed. Screen captures of the SDSS are presented in Appendix B.

4.2. Conceptual Design

From an abstract perspective, a decision support system framework has four generic components that are basic elements of any DSS which include (1) a language system, (2) a presentation system, (3) a knowledge system, and (4) a problem-processing system (Bonczek, Holsapple, and Whinston, 1980; Bonczek, Holsapple, and Whinston, 1981, Dos Santos and Holsapple, 1989, Holsapple and Whinston, 2001). The language system and presentation system consist of requests and responses the decision support system can accept and emit. The knowledge system contains the information or intelligence the DSS has stored and retained (Holsapple and Whinston, 2001). These three components by themselves are incapable of performing decision support tasks, but rather represent the capabilities of the decision support system. The fourth system, the problem-processing system is the active component that coordinates the interaction between the language system, the presentation system, and the knowledge system. The interaction between these four components is illustrated in Figure 4.1.

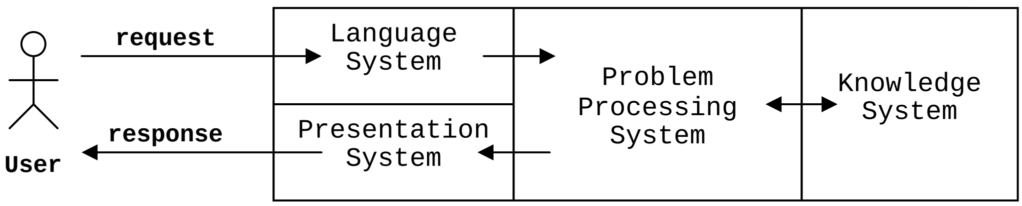


Figure 4.1 Components in a generic decision support system (from Holsapple and Whinston, 2001)

A Spatial Decision Support System can be considered as a subtype of the generic decision support system described by Holsapple and Whinston (2001). Collectively, the individual components perform functions assisting users in the decision process. The problem processing system of the generic DSS contains application logic developed from the use-cases presented above and controls the sequence in which components are called and data are passed. This application logic is housed on the server and acts as the intermediary between the client and the SDSS components. It receives the request from the language system containing instructions for what the user wants performed and returns information to the presentation system, which are passed to the client. The knowledge system components are comprised of geoprocessing components, Internet GIS, a relational database management system, and simulation modeling technology. Geographic Information System technology is used in Internet GIS and geoprocessing components allowing spatial data to be viewed through the Internet, and geoprocessing capabilities to be embedded in the application. Figure 4.2 illustrates a high level perspective of the Spatial Decision Support System architecture and a detailed discussion of each component is presented below.

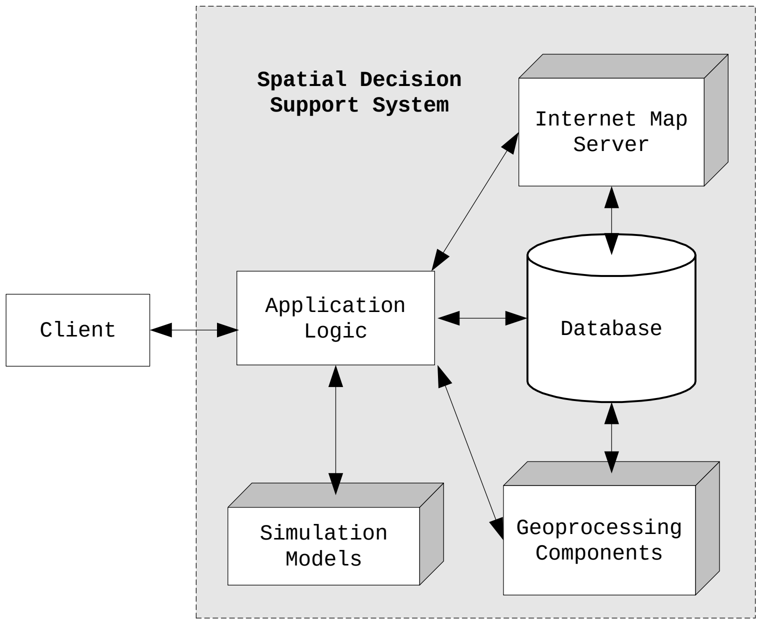


Figure 4.2 Conceptual Overview of the Spatial Decision Support System

4.2.1. Internet GIS – Internet Map Server

To provide users with a spatial perspective, an Internet map server is used to produce images that are presented to the client. The map server produces images using spatial data retrieved from both local drives and the database management system. The spatial decision support system generates a new image based on how the user interacts with the client application. For example, the SDSS allows users to toggle spatial layers on and off, change the perspective of the map, and change the order of the map layers. The map server also generates images that contain dynamically generated spatial data; after simulations are performed, results are added to a map image and returned to the client.

4.2.2. Geoprocessing Components

The geoprocessing components provide the capability to perform hydrologic analysis and prepare model parameters along with simulating effects of rangeland management practices. These components have embedded GIS functions giving users access to GIS technology without the complexities or expense of using commercial off the shelf products. The geoprocessing components in the SDSS perform watershed boundary delineation, topographic parameterization, land cover parameterization, soils parameterization, and estimate livestock distribution and impacts.

4.2.3. Simulation Models

A primary knowledge source in the spatial decision support system is the hydrologic simulation model that encapsulates decades of research on the fundamental hydrologic processes. The SDSS contains the Kinematic Runoff and Erosion Model (KINEROS; Smith et al., 1995) which has a long history of applications in southwestern Arizona (Woolhiser et al., 1990; Goodrich, 1991; Miller et al., 2002). Detailed information on KINEROS is presented in Appendix C. Within the SDSS, the simulation model components estimate the impact of management on runoff and erosion from user-selected watersheds. Future additions to the SDSS will include the Soil Water Assessment Tool (SWAT; Arnold et al., 1998) and the Arid Basin Model (ARDBSN; Stone et al., 1986).

4.2.4. Database Management System

The Database Management System contains both global and user specific information. The global information consists of both spatial and aspatial data that are used to perform simulations. Data such as land cover and soils datasets capture the variability of physical parameters through space that are incorporated into the modeling process. Examples of aspatial data include the hydrologic parameter values relating the physical properties of the vegetation or soils to model input parameters.

The Entity Relationship Diagram (Figure 4.3) provides a conceptual view of the database design. The complicated aspects of the design result from dependencies in hydrologic modeling parameters on simulation models, i.e. model parameters derived for one simulation model do not apply for a different simulation model. The description of the model parameter domain begins with the BOUNDARY entity that contains delineated watershed boundaries created from one of the geoprocessing component discussed above. A watershed boundary can be subdivided multiple times, each of which is referred to as a topographic parameter set (TOPOPARAMSETS) that contains metadata about the discretization process. Each topographic parameter set (TOPOPARAMSETS) can have many subwatersheds (SUBWATERSHEDS) representing the polygonal modeling element of the watershed. Each modeling element (SUBWATERSHEDS) has associated topographic parameters (TOPOPARAMETERS) such as average slope, centroid, width etc. Each topographic parameter set (TOPOPARAMSETS) can have multiple soils and/or land cover parameter sets (SOILSPARAMSETS, LANDCOVPARAMSETS), where each contains multiple soils and land cover model parameters (SOILSPARAMETERS, LANDCOVPARAMETERS), respectively. Each of these parameter values is associated with one and only one of the subwatershed elements. Each soils and land cover parameter set is associated with a respective look-up table (SOILS_LUT, LANDCOV_LUT) that contains relationships between model parameters and soils and vegetation classes.

The management systems (MANAGEMENT_SYSTEMS) stored in the Database Management System are comprised of predefined management practices. These management practices are therefore subclasses into the three management practices currently supported by the Spatial Decision Support System, pasture boundaries, water points, and sediment detention structures. Each of the three supported best management practices has a spatial component that is stored as attribute in the DBMS along with their aspatial attributes.

4.2.5. Application Logic

Where appropriate, the application architecture is structured using design patterns which are solutions to commonly recurring problems in software design. The three key design patterns used in the development of the Spatial Decision Support System are the Model-View-Controller, Session Façade, and Data Access Object patterns. The Model-View-Controller (MVC) pattern is a common structure for web-based applications where the application logic is decoupled into model, view, and controller components. The “model” component contains the business logic used in the application while the “view” contains the presentation component for the application. The “controller” component is the messenger between the user or “view” and the business logic or “model.”

The Session Façade pattern is a structure that abstracts the server-side Entity Enterprise Java Beans (EJBs), only allowing the Entity EJBs to communicate with session beans. This pattern provides the benefits of low network overhead, low coupling, and good reusability (Marinescu, 2002). With this pattern, each use case is implemented using a single session bean that coordinates the communication with other session and entity beans; therefore, the client is only required to make one network call for the logic of a use case to be performed.

The Data Access Object pattern is a common pattern used to transfer data between components by making a single fine-grained method call. Furthermore, these objects abstract and encapsulate all access to the data allowing the source of the data to change without requiring the client's interaction to change (Alur et al., 2001).

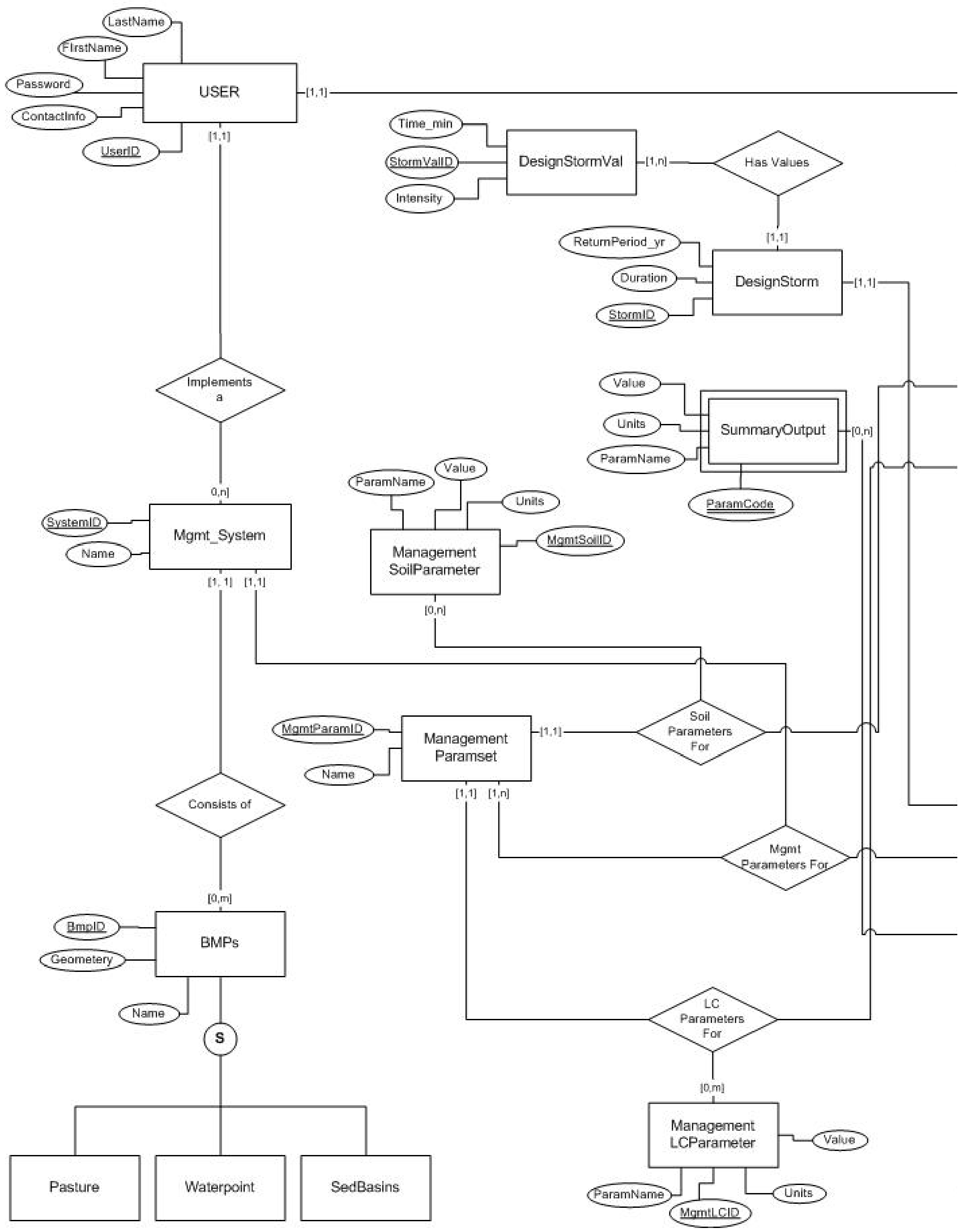


Figure 4.3 Entity-Relationship diagram for the spatial decision support system.

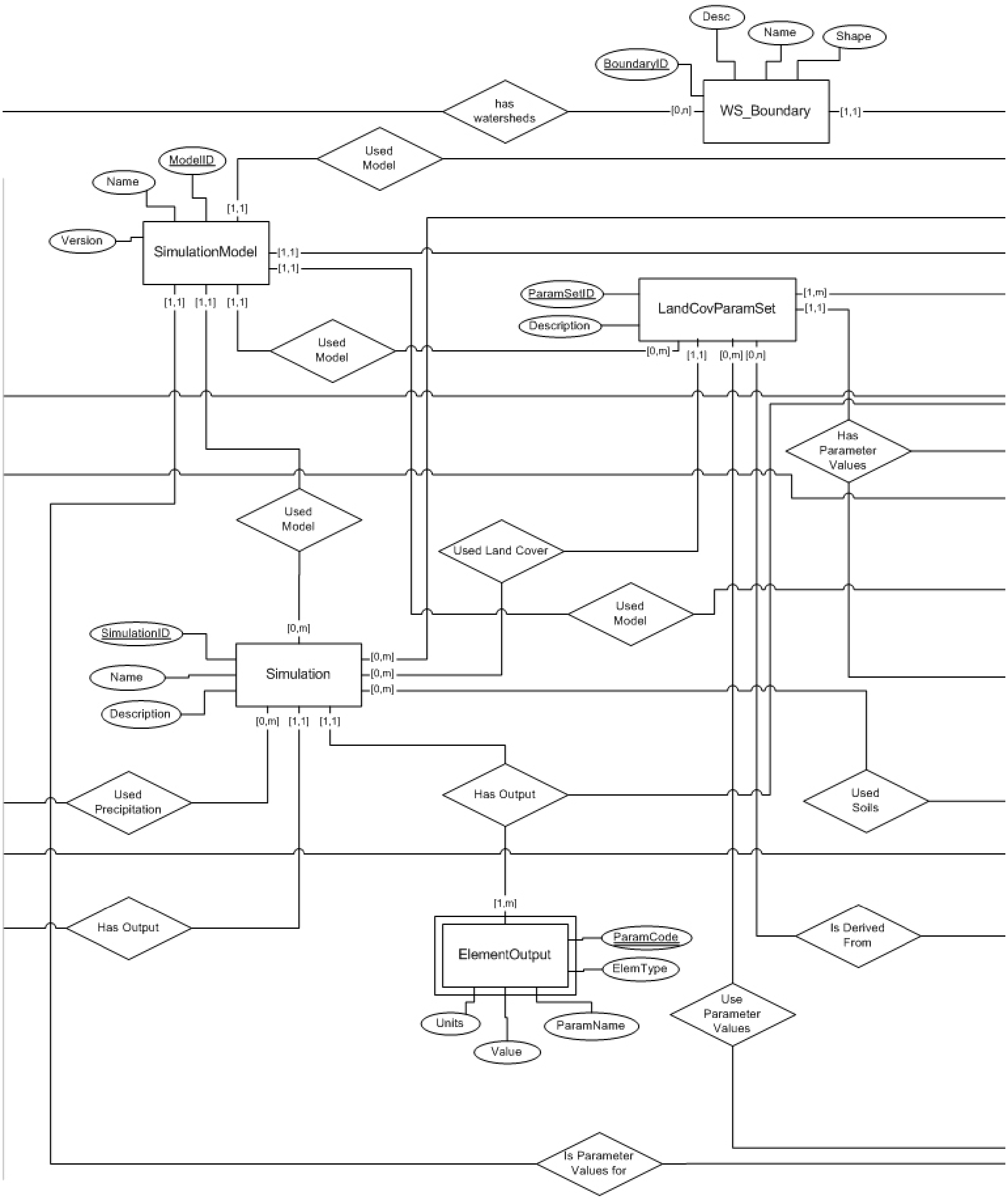


Figure 4.3 (cont-1)

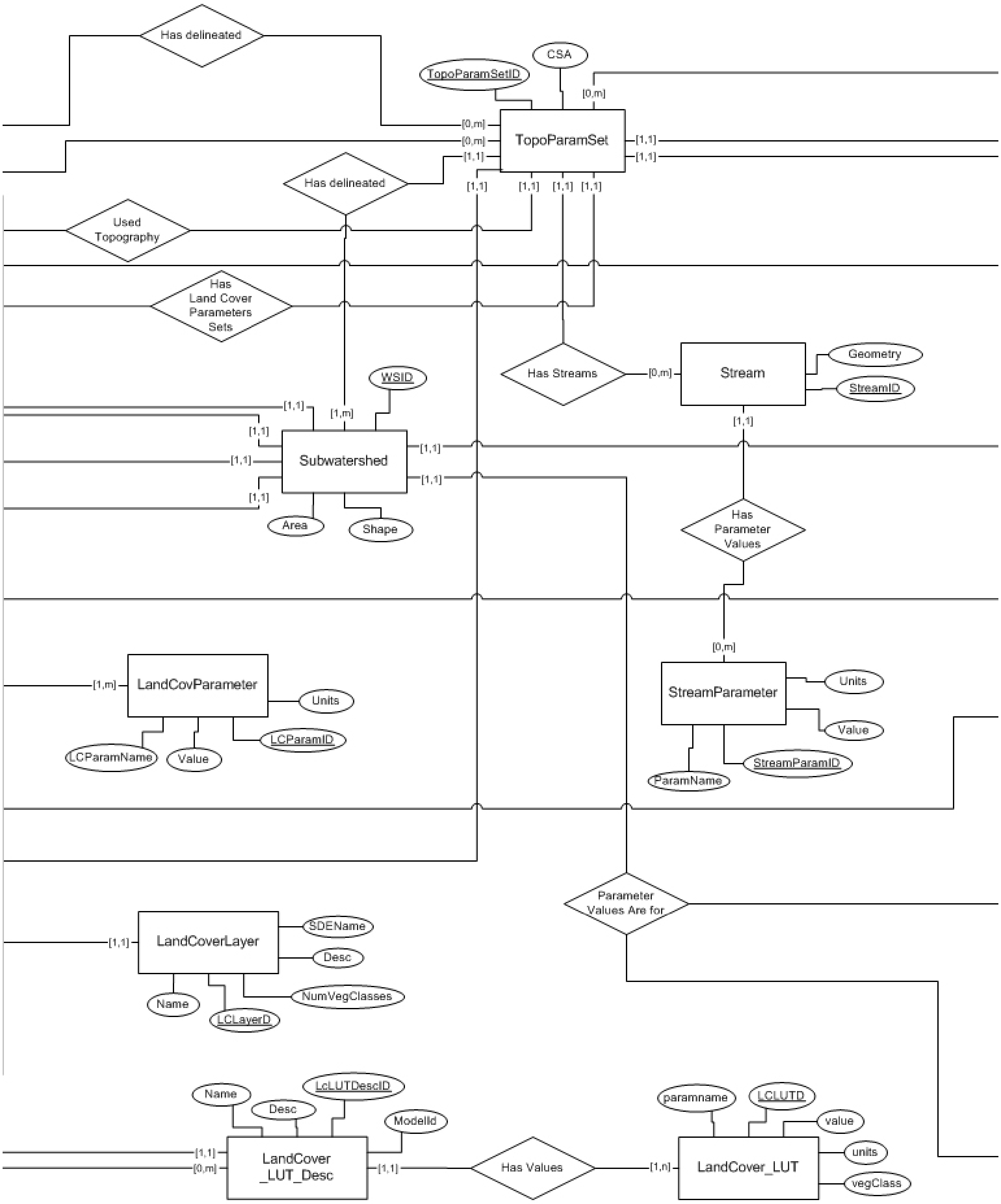


Figure 4.3 (cont-2)

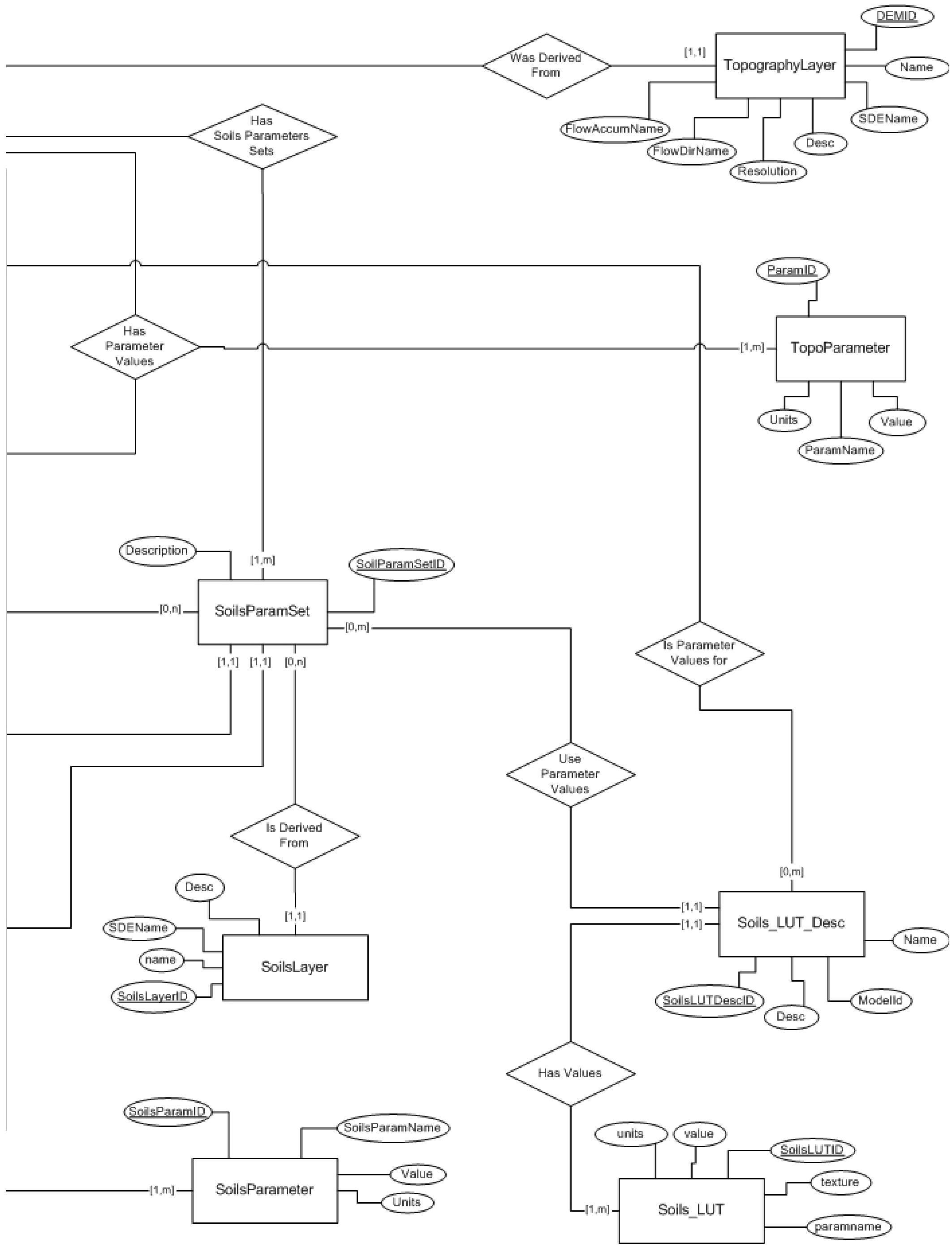


Figure 4.3 (cont-3)

4.3. Implementation

4.3.1. Database Management System

Converting the entity relationship diagram to a relational schema was performed through a number of steps. The first step was to create a table for each entity class. Secondly, the management practices subclass was translated into tables by making each management practice a separate table, which was done because each practice has different attributes and different shape types (i.e. a point for water sources and polygons for pastures and sediment detention structures). Finally, the relationships were incorporated by including foreign keys in the necessary tables. The implementation consists of twenty-five tables that are listed below (Table 4.1) with a data dictionary presented in Appendix D.

Table 4.1 List of tables used in the Spatial Decision Support System.

ELEMENT_OUTPUT(SIMID, ELEMENTID, TYPE, PARAMCODE, PARAMNAME, VALUE, UNITS)
LANDCOVERLAYERS(LANDCOVLAYERID, NAME, SDENAME, DESCRIPTION, NUMVEGCLASSES)
LANDCOVPARAMETERS(LCPARAMID, SUBWATERSHEDID, PARAMETERNAME, VALUE, UNITS, LCPARAMETERSETID, TOPOPARAMSETID)
LANDCOVPARAMSETS(LCPARAMSETID, MODELID, LCLAYERID, DESCRIPTION, TOPOPARAMSETID, LANDCOVLUTID)
LANDCOV_LUT(LCLUTID, CLASS, PARAMNAME, VALUE, UNITS, LCDESCID)
LANDCOV_LUTDESC(LCDESCID, NAME, MODELID, DESCRIPTION)
MANAGEMENT_SYSTEMS(SYSTEMID, NAME, USERID, BASE_TOPOPARAMSETID, MGMT_TOPOPARAMSETID)
MGMT_SOILSPARAMETERS(MGMTSOILSPARAMID, SUBWATERSHEDID, PARAMETERNAME, VALUE, UNITS, BASETOPOPARAMSETID, MGMTTOPOPARAMSETID)
PARAMETER_FILE(PARAMID, USERID, MODELID, WSHEDID, SCENARIOID, DESCRIPTION, XMLFILE)
PASSWORD(USERID, PASSWORD)
PASTURE(PASTUREID, USERID, RANCHID, PASTURE_GEOM)
PASTURES_IN_WATERSHED(WATERSHEDID, PASTUREID)
RANCH(RANCHID, RANCHNAME)
SIMULATIONS(SIMID, MODELID, TOPOPARAMSETID, SOILSPARAMSETID, LCPARAMSETID, NAME, DESCRIPTION)
SIMULATION_MODEL(MODELID, NAME, VERSION)
SOILSLAYERS(SOILSLAYERID, NAME, SDENAME, DESCRIPTION)
SOILSPARAMETERS(SOILSPARAMID, SUBWATERSHEDID, PARAMETERNAME, VALUE, UNITS, SOILSPARMETERSETID, TOPOPARAMSETID)
SOILSPARAMSETS(SOILSPARMSETID, MODELID, SOILSLAYERID, DESCRIPTION, TOPOPARAMSETID, SOILSLUTID)
SOILS_LUT(SOILSLUTID, TEXTURE, PARAMNAME, VALUE, UNITS, SOILSDESCID)
SOILS_LUTDESC(SOILSDESCID, NAME, MODELID, DESCRIPTION)
STREAM(SCENARIOID, STREAMID, WATERSHEDID, STREAM_GEOM)
STREAMPARAMETERS(STREAMPARAMID, STREAMNUMBER, PARAMETERNAME, VALUE, UNITS, TOPOPARAMSETID)
SUBWATERSHEDS(TOPOPARAMSETID, SUBWATERSHEDID, SHAPE, AREA)
SUMMARY_OUTPUT(SIMID, PARAMCODE, PARAMNAME, VALUE, UNITS)
TOPOGRAPHYLAYERS(DEMID, NAME, SDENAME, RESOLUTION, DESCRIPTION, FLOW_DIR_SDENAME, FLOW_ACCUM_SDENAME)
TOPOPARAMETERS(TOPOPARAMID, PARAMNAME, VALUE, UNITS, TOPOPARAMSETID, SUBWSHEDID)
TOPOPARAMSET(TOPOPARAMSETID, CSA, DEMID, WATERSHEDID)
USERS(USERID, EMAIL, FIRSTNAME, LASTNAME, STADDRESS1, STADDRESS2, CITY, STATE, ZIP, COUNTRY, PHONE)
WATERSHED_BOUNDARY(WATERSHEDID, USERID, WATERSHEDNAME, DESCRIPTION)
WATERSHED_SCENARIO(SCENARIOID, NAME, DESCRIPTION, USERID)

4.3.2. Geoprocessing Components

The geoprocessing components in the Spatial Decision Support System are developed using ESRI ArcObjects (ESRI, 2000) components that are deployed as Web services (See Appendix D for design information). Web services are modules that communicate using text (XML) based messages. This Web services architecture eliminates programming language, operating system, database management system, and hardware dependencies. Furthermore, communication is conducted over Hypertext Transfer Protocol (HTTP), simplifying the development of distributed applications. Web services simplify the process of incorporating legacy applications into the information systems by providing a standard interface for all components.

Four geoprocessing components are included in the spatial decision support that create spatial data based on a user’s request, prepare modeling parameters using digital data layers, and estimate environmental impacts of management systems.

§ ***Watershed boundary delineation***

The watershed boundary delineation component allows users to create watershed catchments based on an outlet location. This component uses spatial data to calculate flow paths for a given catchment. The Web service component requires the x- and y-coordinates of the watershed outlet, a watershed boundary name, and a watershed boundary description and it returns a primary key for the newly created boundary which is stored as a spatial object in the database. An example watershed delineation message is presented in Figure 4.4.

```
<?xml version="1.0" encoding="UTF-8" ?>
<SOAP-ENV:Envelope xmlns:SOAP-
ENV="http://schemas.xmlsoap.org/soap …. >
  <SOAP-ENV:Body>
    <ns1:CreateBoundary
xmlns:ns1="http://tempuri.org/message/" …  >
      <outnumber xsi:type="xsd:string">1311</outnumber>
       <outletX xsi:type="xsd:double">581716.091</outletX>
       <outletY xsi:type="xsd:double">3511404.965</outletY>
       <username xsi:type="xsd:string">SDSSUSER2</username>
       <boundaryName xsi:type="xsd:string">Watershed
1</boundaryName>
       <boundaryDesc xsi:type="xsd:string">Watershed 1
Desc</boundaryDesc>
    </ns1:CreateBoundary>
  </SOAP-ENV:Body>
</SOAP-ENV:Envelope>
```


Figure 4.4 The spatial decision support system for rangeland watershed management uses geoprocessing Web services which are components that communicate through text messages. This text message is sent to the watershed delineation component and includes a unique number, outlet location, name, and description. The Web service performs the watershed delineation and returns the boundary to the client.

§ ***Topographic parameterization***

For each watershed boundary that is delineated, the boundary is subdivided into hydrologic modeling elements based on flow paths. These modeling elements are considered hydrologically homogeneous units which assumes each element has uniform topographic, soil, and land cover parameters. The subdivision of the watershed boundary is dependent on the ontological representation required by the hydrologic simulation model. Two common ontological representations are the “open book” (Figure 3.2a) and the basin wide (Figure 3.2b) discretization. An open book representation subdivides the watershed so each stream element has lateral upland planes and either an upland zero-ordered watershed or upland contributing channels. A basin wide discretization has one lateral element for each stream channel and if the basin is a first order basin, the stream channel does not have a contributing element, otherwise the stream channel has a contributing stream element. KINEROS uses the “open book” approach which is the only configuration currently available in the SDSS.

The topographic parameterization Web service has two different methods that require different sets of input requirements to perform the operation discussed above. The simplest method accepts a watershed boundary identification and a username. This method uses defaults for the input digital elevation model, flow direction grid, flow accumulation grid, and discretization complexity. The other method allows client applications to specify the input digital elevation model, flow direction grid, flow accumulation grid, and discretization complexity.

§ ***Land cover and soils parameterization***

The land cover parameterization component estimates parameters derived from digital land cover layers for simulation models. The land cover layers used in this parameterization routine are raster format where each cell corresponds to a vegetation type. For each watershed modeling element created in the topographic parameterization routine, the percent of each vegetation class is calculated and the model parameter values for all the vegetation classes in the element are area weighted. For example, if a modeling element has 25% forest, 25% urban, and 50% grassland land cover types, the associated model parameter value for the current element is the sum of 0.25 of the forested parameter value, 0.25 of the urban parameter value, and 0.50 of the grassland parameter value. The Web service method requires the client to specify the topographic parameter set to parameterize, the land cover layer to use in the parameterization, a description of the parameterization, the model that the parameterization will support, and the look-up table to use in the parameterization process.

Similar to the land cover parameterization, the soils parameterization routine estimates model specific soil parameter values for the hydrologic simulation model. The routine calculates the percent of a soil texture class in each modeling element and weights the model specific parameters accordingly. The Web service method requires the topographic parameter set to parameterize, the soils layer to use in the parameterization, the simulation model the parameterization will support, a description of the soils parameterization, and a look-up table relating the soil texture values to model specific parameters.

§ ***Livestock distribution and impacts***

The simulation of livestock distribution and resulting environmental impacts is a modification of the RANGEMAP

(Guertin et al., 1998) spatial application. The spatial decision support system contains routines from RANGEMAP that estimate the distribution of livestock given pasture boundaries and water points. The relationships used to estimate the distribution of cattle are presented in Tables 4.1 and 4.2. Additional information on RANGEMAP implementation is presented in Appendix F.

Table 4.2 Reductions in Grazing Capacity with Distance to Water (From Table 8.8 in Holecheck et al., 1995)

Distance From Water		Percent Reduction in Grazing Capacity
Miles	**Kilometers**	
0 - 1	0 - 1.6	0
1 - 2	1.6 - 3.2	50
> 2	> 3.2	100 (Considered Not Grazed)

Table 4.3 Reductions in Grazing Capacity with Percentages of Slope(From Table 8.8 in Holecheck et al., 1995)

Percent Slope	Percent Reduction in Grazing Capacity
0 - 10	0
11 - 30	30
31 - 60	60
> 60	100 (Considered Not Grazed)

Given the relationships in Tables 4.1 and 4.2, the spatial distribution of grazing intensity is estimated and infiltration rates of the soil are modified according to grazing intensity relationships found by Gifford and Hawkins (1978). Gifford and Hawkins (1978) examined the literature and developed “rough, approximate rules” for “average reaction for porous soils” stating that heavily grazed areas reduced infiltration capacity by approximately one-half of the infiltration capacity in ungrazed conditions and moderately and lightly grazed areas reduced infiltration capacity by approximately one-quarter compared to ungrazed conditions. The modified soil parameters for each modeling element are stored in the database for future simulations.

4.3.3. Internet Geographic Information Systems

The spatial decision support system utilizes ESRI’s ArcIMS Internet GIS technology (ESRI, 2003b). ArcIMS has a Java application programming interface (API) that allows the spatial decision support system to control the creation of new maps. Certain classes within the Java API were subclassed to provide specific behavior unique to the SDSS.

For example, the Map class in the ArcIMS Java API was subclassed to a SDSSMap class which includes functionality to add watershed boundaries provided a boundary identifier, and add simulation results provided a simulation identifier.

4.3.4. Simulation Models

The Kinematic and Erosion Model (KINEROS) is deployed as a Web service external to the spatial decision support system. Since KINEROS is a DOS executable program, a Java wrapper was created to coordinate the operation of the model. The Web service takes a series of strings that include the input parameters, the input precipitation, and a number of control parameters. The wrapper converts these string values to text files stored on disk and initializes the KINEROS model. Once the model simulation is complete, the wrapper reads the model output and returns the simulation results to the calling component.

4.3.5. Application Logic

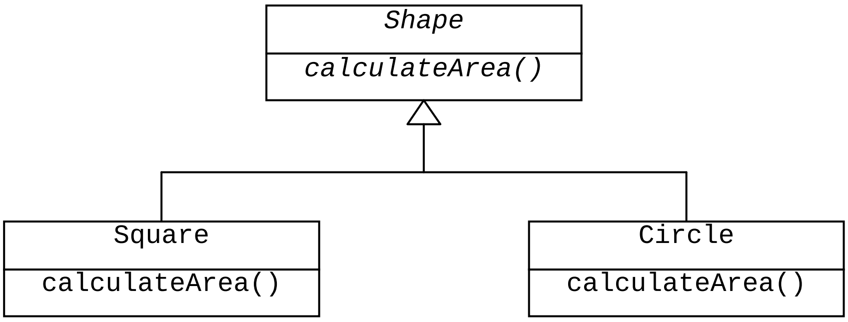
The Spatial Decision Support System is implemented using twenty Enterprise JavaBeans (EJB) which are server-side software components that can be deployed in distributed multi-tier environments (Roman et al., 2002). There are three types of EJBs, session beans which model the business process, entity beans which provide an object-oriented view of the database, and message-driven beans which are similar to session beans except that they communicate with messages. Additional design information is available in Appendix E.

4.4. Evaluation of Design Goals

In addition to the functional requirements presented in Chapter 3, the application is required to be extensible, interoperable, accessible, and secure. An extensible SDSS allows new simulation models and management practices to be easily added. Interoperability promotes the reuse of SDSS components by other applications. The SDSS must be accessible so that users without geographic information software or extensive background knowledge of GIS can access and use the application. And finally, the SDSS must be secure so that users are comfortable storing sensitive data. While these design objectives are difficult to measure quantitatively, the steps taken to meet the objectives are discussed below.

4.4.1. Extensible

As discussed in the spatial decision support system requirements, the application must allow new models to be easily incorporated into the decision processes. As new models are developed or new concerns are addressed by the SDSS, simulation models need to be added without requiring the existing application to be modified significantly. This objective is accomplished using the object-oriented principles of inheritance and polymorphism. Inheritance is the concept of deriving new classes from existing classes, and the invocation of the appropriate object method depending on where the object is in the inheritance hierarchy is polymorphism (Horstmann and Cornell, 1999). These topics are best illustrated with a simple example. An interface Shape is defined that has one method calculateArea() that returns the area of the shape. Two concrete classes Square and Circle inherit the Shape interface. Because each shape has a different formula for calculating it's area, each must implement the calculateArea() method (Figure 4.4a). Once this inheritance hierarchy is set up, a Shape object reference can either be assigned to a Square or a Circle object and when the calculateArea() method is called, the appropriate implementation of calculateArea() is executed (Figure 4.4b)



(a) Classes Square and Circle inherit the superclass Shape

```
// Create two Shape references
Shape s1  = null;
Shape s2  = null;

// assign one of the shape references to a new Square
// and one to a new Circle object.
s1 = new Square();
s2 = new Circle();

// calling the calculateArea method on the Shape
// reference calls the corresponding method on the
// Square and Circle objects
s1.calculateArea();  // calls calculateArea() on the
Square object
s2.calculateArea();  // calls calculateArea() on the
Circle object
```

(b) Instantiating an object using the superclass reference with a subclass implementation allows polymorphic calls on the reference

Figure 4.5 Example of object-oriented concepts of inheritance and polymorphism

The object-oriented concepts of inheritance and polymorphism are used in the design and implementation of the Spatial Decision Support System to allow new simulation models to be added to the application. In a similar manner to the example above, interfaces and abstract base classes are defined through the application. The models incorporated into the Spatial Decision Support System have common features that allow an object-oriented hierarchy to be developed. Each simulation model has the capability to be run given the appropriate input files and model control files and produces simulation output. Within an object-oriented framework, these characteristics can be represented using the following interfaces depicted in Figure 4.5. Therefore, any simulation model that is included in the Spatial Decision Support System must include classes that implement these four interfaces.

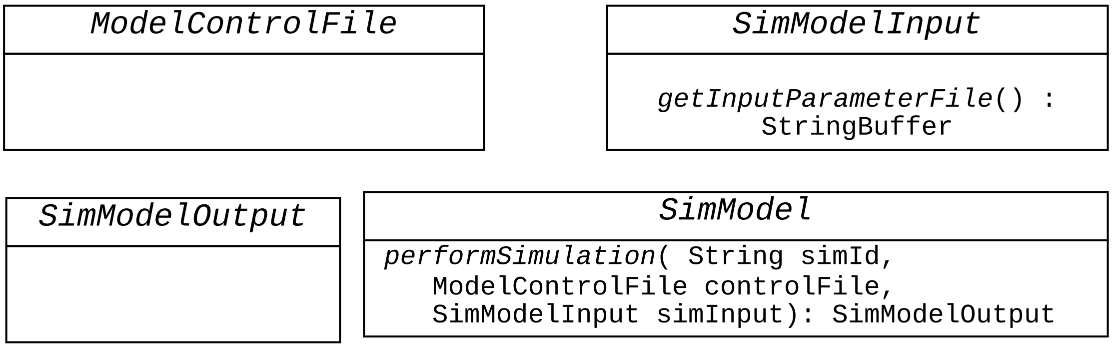


Figure 4.6 Interfaces used to incorporate simulation models into Spatial Decision Support System.

In addition, the Factory Design Pattern (Eckel, 2001) is used to centralize the creation of objects for new simulation model components. To include a new model, a subclass of *ModelFactory* must be created that overrides the four abstract methods, getSimModel, getSimModelInput, getModelName, and getModelControlFile. An important component of the abstract class ModelFactory is that it contains a static method factory. Static methods are class methods rather than instance or object methods meaning that an instance is not required for a static method to be called. This is important because the ModelFactory class is abstract and therefore an instance of ModelFactory cannot be created. Furthermore, the implementation of the factory method of ModelFactory determines what the appropriate type or subclass of ModelFactory should be returned based on the parameters passed into the factory method.

ModelFactory
getSimModel() : SimModel *getSimModelInput() : SimModelInput* *getModelName() : String* *getModelControlFile() : ModelControlFile* factory(String simId, String soilsParamsetId, String landcovParamsetId, HashMap simulationControlParameters) : ModelFactory

Figure 4.7 Abstract class used to generate new ModelFactory objects for incorporating new simulation models into the Spatial Decision Support System.

An implementation of this design can be illustrated by examining the inclusion of the Kinematic Runoff and Erosion (KINEROS: Smith et al., 1995) model in the Spatial Decision Support System. The four interfaces discussed above are implemented by four instantiable classes, KinerosControlFile, KinerosSimModel, KinerosSimModelInput, and KinerosSimModelOutput (Figure 4.7). Since the four interfaces do not provide any implementation details, the four subclasses provide the KINEROS-specific implementation instructions for how to include the model into the Spatial Decision Support System.

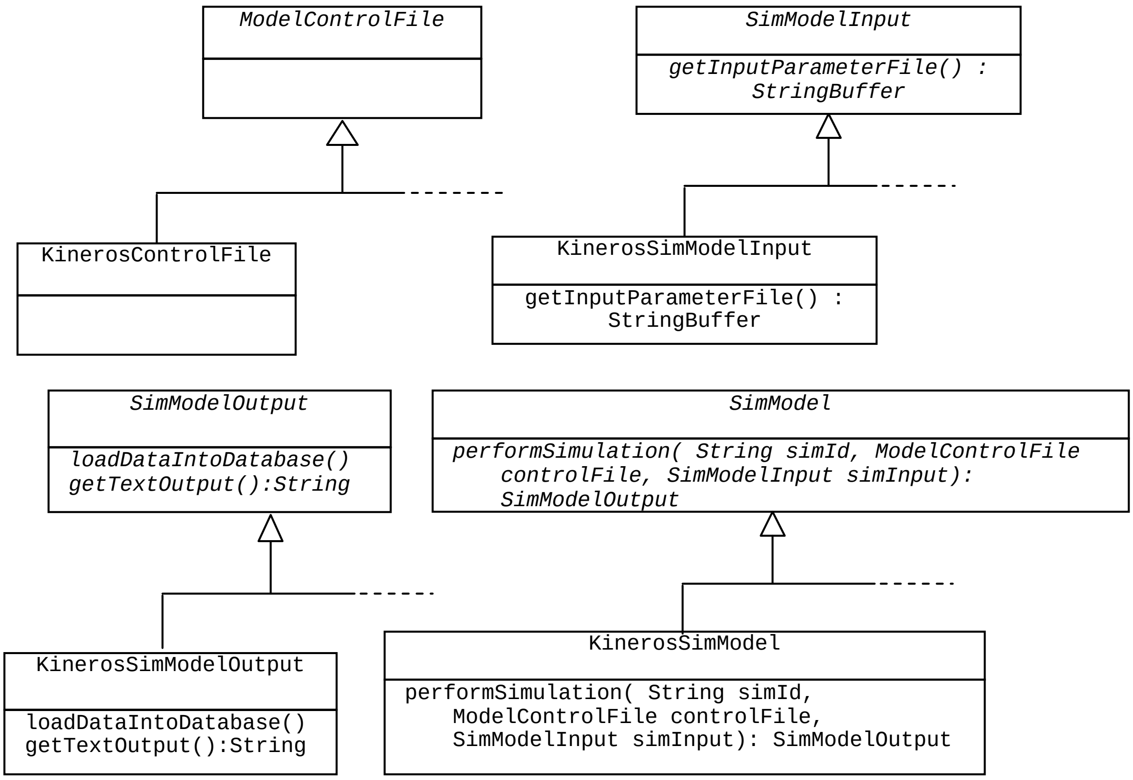


Figure 4.8 Class inheritance tree for including Kinematic Runoff Erosion Model in the Spatial Decision Support System.

Since the implementation code is now incorporated using the KINEROS-specific four subclasses, the next and final step is to create the KINEROS-specific implementation of the ModelFactory abstract class. Subclasses of ModelFactory must implement four methods: getSimModel which returns a SimModel object, getSimModelInput which returns a SimModelInput object, getModelName which returns a String object, and getModelControlFile which returns a ModelControlFile. The KINEROS subclass of ModelFactory, KinerosModelFactory (Figure 4.8), creates and returns the KINEROS implementations of the four interfaces described above.

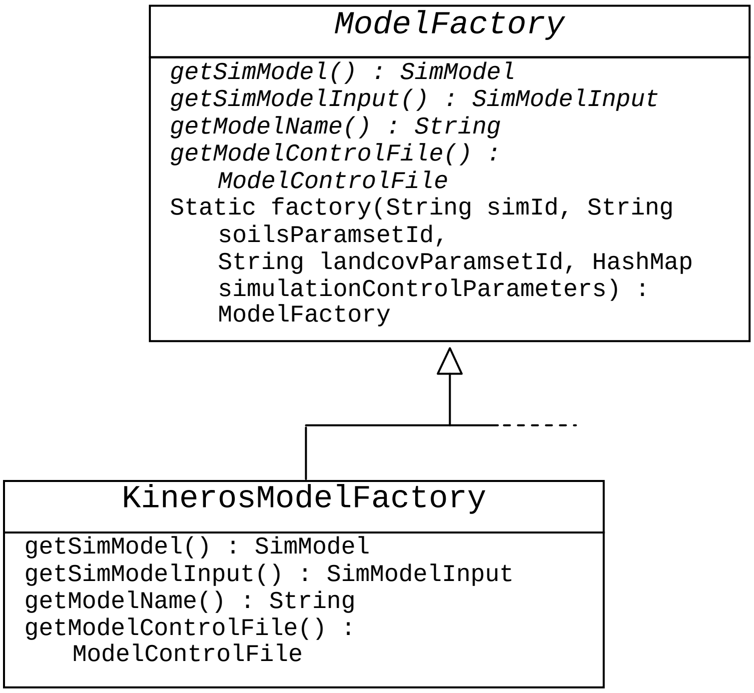


Figure 4.9 The ModelFactory abstract class must be extended for the KINEROS-specific implementation which controls the instantiation of the KINEROS implementation of the SimModel, SimModelInput, and ModelControlFile interfaces.

4.4.2. Interoperable

The utilization of Web services in the design and implementation provides components that can be included into other applications. As previously mentioned, Web services are components that communicate using text-based messages and therefore eliminate proprietary communication and data protocols. Since all of the geoprocessing components are published as Web services, they could be included in other applications. For example, if a GIS developer in Phoenix needs a watershed boundary created given a watershed outlet, they could leverage the CreateBoundary Web service in the spatial decision support system rather than creating a duplicate component to perform the same task.

4.4.3. Accessible

The spatial decision support system is made accessible through the Internet, minimizing the application maintenance required by users. Providing access to these applications opens doors to future research to evaluate the role of technology in bottom-up decision-making for watershed management. As stated previously, successful bottom-up decision making hinges on educating stakeholders. This type of application provides a resource to inform decision makers about the problems, and allows them to design and evaluate potential management alternatives to identified problems.

While deploying watershed management applications via the Internet greatly increases availability to users, less than half or over 61.6 million (41.5% in August 2000) of all American households do not have access to the Internet (NTIA and ESA, 2000). Moreover, Internet access is unequally distributed across the United States, with access in rural areas lower than urban areas. Therefore, rural stakeholders will be forced to find other alternatives such as public libraries to get access to Internet applications. However, the digital divide between the *"haves"* and the *"have nots"* is narrowing. More importantly for watershed management, the gap between households with internet access in rural areas and the nationwide average has narrowed from 4.0 percentage points in 1998 to 2.6 percentage points in 2000 (NTIA and ESA, 2000). In rural areas, 38.9% of the households had Internet access; a 75% increase from 22.2% in December 1998.

4.4.4. Secure

Different users will have different objectives for using the spatial decision support system; some users will use the SDSS for management decision-making while other users will curiously explore the application's functionality. As a consequence, a security framework is implemented to allow users developing management systems to access their data while not hindering the experience for those exploring the capabilities of the SDSS, who do not require user specific data to be stored and retrieved. To accomplish this goal, the SDSS uses a form-based authentication approach requiring users to sign-in to save simulation data for the current session and retrieve management scenarios from a previous session; however, users not signed-in are provided with the same functionality for a session. Form-based authentication is commonly used in ecommerce sites such as Amazon.com where users can browse and retrieve information on books but are required to sign-in for purchases.

4.5. Summary of the Benefits of the SDSS

The Spatial Decision Support System provides a number benefits compared to other decision support systems resulting from its architecture and deployment methods. The incorporation of Web services in the deployment of the components provides the first series of GIS Web services tailored for watershed management. Utilizing this framework simplifies the development of applications in the future that are capable of leveraging these components. In addition, the Spatial Decision Support System minimizes the input parameter values required from users, one of the deterrents in the adoption of decision support systems identified by Uran and Janssen (2003) and Newman et al. (2000). Integrating the geographic information system into the application allowed the majority of the parameter values required by the simulation models to be derived from readily available digital data layers. Furthermore, the use of both Internet GIS and geoprocessing Web services provided access to these technologies to users who typically do not have access.

The design of the Spatial Decision Support System provides an easy means for users to define spatially explicit management alternatives. Users create alternatives through an intuitive interface, drawing and attributing management practices on a map. Estimates of sediment yield can be produced for these user defined management system using process based, hydrologic simulation models. Users are also capable of comparing management systems to determine which system produces the lowest estimated sediment yield for a given location.

CHAPTER 5

QUANTIFYING ERROR IN DIGITAL ELEVATION MODELS

5.1. Introduction

Incorporating hydrologic simulation models into the watershed decision making process is a complex procedure. Decision makers are required to have an understanding of the problems and the physical processes causing the problems. Abstracting the physical watershed characteristics into model parameters requires detailed knowledge of model process representation which exceeds the capabilities of many decision makers. Automated applications such as the Spatial Decision Support System simplify the process, providing an opportunity to leverage advances in science into the decision process.

Even though fundamental equations in the core hydrologic models are based on decades of scientific research, hydrologic modeling output contains a tremendous amount of uncertainty. This uncertainty stems from multiple sources, including errors in input data and our inability to represent complex physical processes with mathematical equations. Because of this uncertainty, multiple simulations are required to capture this uncertainty in modeling results.

The automated procedures included in the Spatial Decision Support System allow managers to systematically explore the solution space more easily than stand-alone modeling applications. The SDSS contains a database to potentially store hundreds or thousands of simulations allowing these results to summarized and presented to users. These “bulk simulations” can explore errors resulting from different input GIS data layers, different look-up parameter values, and different precipitation event sizes and distributions. Bulk simulations are nearly impossible using stand-alone models due to the complexities in model parameterization and management of output. The SDSS could also be used in optimization routines because both input and output are controlled by the application.

As stated previously, one of the sources of uncertainty that has an impact on modeling output is input data. Common geographic data used to derive hydrologic modeling parameter values include soils, land cover, and topography. While land cover and soils have been studied by other researchers, the first geographic data set used by the SDSS is a digital elevation model. The DEM is required to delineate watershed boundaries, sub-divide a watershed into modeling elements, and estimate model parameters such as slope and area.

The objective of this chapter is to evaluate and assess the digital elevation models that are used in the spatial decision support system. The analysis is composed of several steps including comparing elevation values of readily available Digital Elevation Models (DEMs) with survey data, comparing DEMs with high-resolution research quality digital elevation models, comparing hydrologic parameters and watershed boundaries derived from different DEMs, and comparing simulation output using the different DEMs with observed data. This analysis uses methodology initially applied in research by Syed (1999), allowing results from this study to be compared with results from the previous research. Furthermore, using the same approach and survey data provides insight into the improvements of readily available digital elevation data through time.

5.2. Walnut Gulch Description

The Walnut Gulch Experimental Watershed is located in southeastern Arizona surrounding the historic town of Tombstone. The 150 square kilometer (57.9 mi^2) watershed was established in the early 1950’s and is maintained and operated by the USDA ARS Southwest Watershed Research Center in Tucson, AZ. Currently, the watershed has 88 precipitation gauges and 29 runoff-measuring sites equipped with electronic sensor/datalogger/radio telemetry configurations allowing the transfer of data from the watershed to the Tucson research station via radio communication on an automated daily schedule. These unprecedented meteorological and hydrological data are complemented with GIS data detailing stream channels (resolution up to 0.5 meters in width), a 10-meter resolution Digital Elevation Model derived from ortho stereophotos, soils data derived from 1:5000 scale aerial photos, along with detailed land ownership, geology, vegetation, and ecological sites layers. For a more detailed description of the hydrology of the Walnut Gulch Experimental Watershed see Renard (1970).

Five watersheds in the Walnut Gulch Experimental Watershed were selected to quantify error introduced from different resolution digital elevation models. These selected watersheds consist of a range of sizes (from 14,800 ha to 4.45 ha) providing a comparison at different scales. All five watersheds have been digitized from aerial photographs providing an estimate of “true” watershed characteristics. The five watersheds (Figure 5.1) are all of Walnut Gulch (WG-1) which is the largest with an area of 14,800 ha, watershed 6 (WG-6) with an area of 9,353 ha, Watershed 11 (WG-11) with an area of 785 ha, watershed 223 (WG-223) with an area of 48.35 ha, and watershed 104 (LH-104) with an area of 4.45 ha.

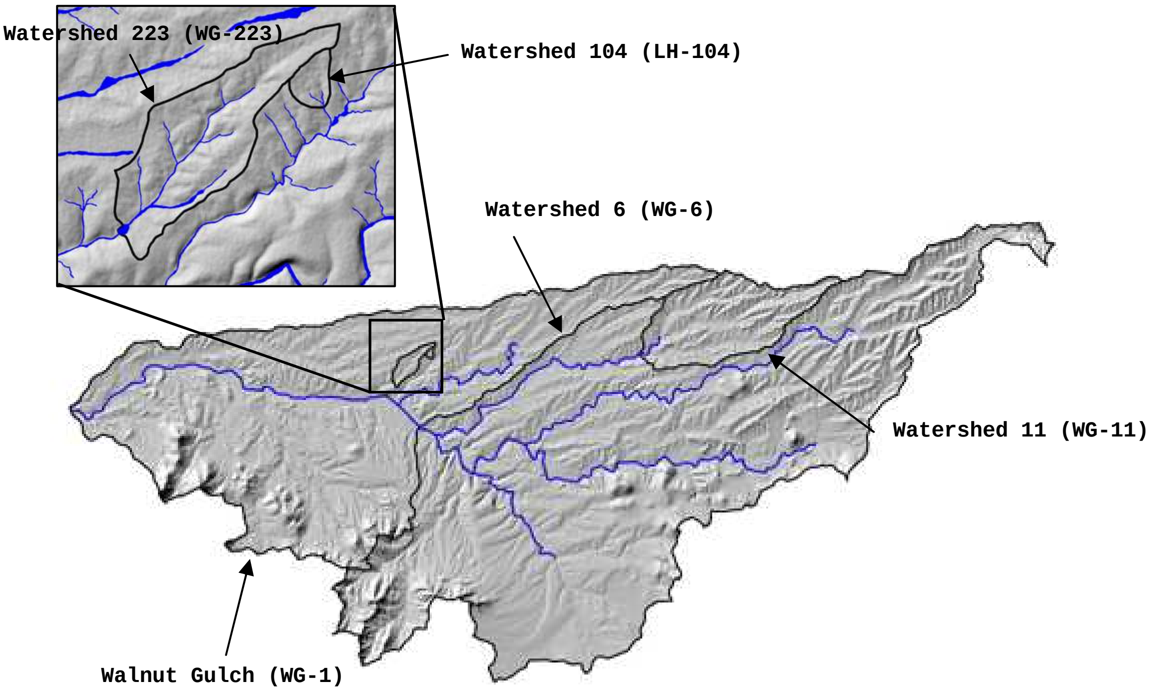


Figure 5.1 Map of simulated watersheds on the Walnut Gulch Experimental Watershed

5.3. GIS Data Sources: Digital Elevation Models

The development of digital elevation models has rapidly advanced during the past few years as new techniques and technologies have been developed to collect, interpolate, and disseminate spatial data. Technologies such as Interferometric Synthetic Aperture Radar (IFSAR), once only used for specialized research purposes, are now being applied to develop broader scale digital data. In addition, improvements in data processing have also led to more accurate spatial models. As computing costs continue to decrease, the availability of digital elevation data has increased dramatically and users now have several choices of DEMs from different agencies. The recently developed DEMs included in this analysis are discussed below.

5.3.1. Walnut Gulch Experimental Watershed Data

Data have been collected on the Walnut Gulch Experimental Watershed in southeastern Arizona over the past five decades. In addition to the extensive stream flow and meteorologic datasets, the watershed contains a rich geospatial database. Three of the digital elevation models incorporated in this analysis were created specifically for research on the Walnut Gulch Experimental Watershed from different data sources and techniques.

5.3.1.1. InterFerometric Synthetic Aperture Radar DEM

Two digital elevation models included in this analysis were derived from InterFerometric Synthetic Aperture Radar data (IFSAR). IFSAR is a modification of the traditional Synthetic Aperture Radar system integrating interferometry techniques to measure the third dimensional points with a high degree of accuracy (Hensley et al., 2001). IFSAR is an active remote sensing system allowing measurements to be obtained at night and under cloud cover. The IFSAR digital elevation models were acquired for Walnut Gulch by the Intermap STAR-3i system in cooperation with Earthwatch Inc. and have been tested to provide a sample spacing of 5 meters or less and a vertical accuracy of approximately 2 meters (Syed, 1999). A 2.5 and a 10 meter DEM were created from these data where the 10 meter DEM was processed with a smoothing algorithm to reduce phase noise (Hensley et al., 2001).

5.3.1.2. 10 Meter Photogrammetric DEM

A 10 meter photogrammetric digital elevation model was created from 1:24000 scale, ortho-rectified aerial photographs taken in 1994 (Miller, 1995). Upland elevation points were extracted at 40 meter intervals and verified with survey locations while the stream network was digitized from 1:5000 meter ortho-rectified aerial photographs. The digital elevation model was created using the TOPOGRID command in ESRI ArcInfo (ESRI, 2000) which generates a hydrologically correct DEM provided elevation points and a stream network. The TOPOGRID command is based on the ANUDEM program developed by Michael Hutchinson (1988, 1989) and uses a spatially varying residual mean square that produces improved results in basin and range topography. The resulting DEM was compared with total station survey points indicating an elevation accuracy of +/- 0.7 meter total height accuracy (Miller, 1995).

5.3.2. United States Geological Survey Elevation Data

Through the National Mapping Program, the United States Geological Survey (USGS) has collected and disseminated elevation datasets since the mid 1970’s and continues to develop data of varying qualities and resolutions (Osborn et al., 2001). The USGS publishes data in “Levels” based on data sources and production method which results in data suitable for different purposes. The first elevation datasets published for a national coverage were Level 1 DEMs which were created photogrammetrically by manual profiling or image correlation techniques from National Aerial Photography Program or equivalent source photographs (7.5 minute DEM Metadata). This first series of elevation data are available for the continental United States and have been replaced by the more accurate Level 2 data.

U.S. Geological Survey Level 2 digital elevation models were created through interpolating contours digitized from 1:24.000-scale or 1:100,000-scale maps and are more accurate compared to Level 1 data. These data are available with either 10 or 30-meter resolutions covering the continental United States.

U.S. Geological Survey Level 3 data integrate all categories of hypsography, hydrography, ridgeline, break line, drain files and all vertical and horizontal control networks (7.5 minute DEM Metadata). Since most uses of U.S. Geological Survey's digital elevation products transcend the 7.5 minute tiles, the USGS developed a National Elevation Dataset (NED) that contains the "best available" topographic data. The NED consists of over 57,000 quadrangle-based DEMs and is updated every two months to incorporate new DEM production (Osborn et al., 2001). Two USGS digital elevation models are used in this analysis, the 30- and 10-meter level 2 DEMs.

5.3.3. Shuttle Radar Topography Mission Elevation Data

The Shuttle Radar Topography Mission (SRTM) data were collected over an eleven-day mission in February, 2000 by the Space Shuttle Endeavour when 99.97% of the Earth's land mass between 57 degrees south and 60 degrees north latitude were mapped using a C-band radar system (Hensley et al., 2001). The mapping mission was conducted by the National Imagery and Mapping Agency (NIMA) and the National Aeronautics and Space Administration (NASA) and provided the first seamless topographic map of the world. For the continental United States and North America, 1-arc second (approximately 30 meter) and 3-arc second (approximately 90 meter) data are available, respectively. However, only the 3-arc second data are currently available for southeastern Arizona and are used in this analysis. To date, this is the best available seamless Digital Elevation Model for the United States and Mexico, key areas in the application of the Spatial Decision Support System.

5.3.4. Digital Elevation Models Analyzed by Syed, 1999.

Research conduced by Dr. Kamran Syed at the Southwest Watershed Research Center in Tucson, AZ quantified the error in readily available digital elevation models. Illustrating how rapidly the quality of data has changed, the DEMs used in Dr. Syed’s research have been improved significantly. Dr. Syed used six digital elevation models in his analysis including a 2.5 meter Interferometric Synthetic Aperture Radar (IFSAR) DEM, a 5 meter DEM created from survey data for a small watershed in Walnut Gulch, a 15 meter DEM created from low level areal photogrammetry for a small watershed in Walnut Gulch, a USGS 30-meter Level 1 DEM, an Agricultural Research Service low level areal photogrammetry 40-meter DEM, and a Defense Mapping Agency 3 arc second (~30 meter) DEM.

Table 5.1 Summary of Digital Elevation Models used in this Analysis

DEM Name	Resolution (m)	Aerial Extent	Source
IFSAR	2.5	Walnut Gulch Experimental Watershed	Interferometric Synthetic Aperture Radar
IFSAR	10	Walnut Gulch Experimental Watershed	Interferometric Synthetic Aperture Radar
USGS	10	Entire United States	USGS Contour Data
USGS	30	Entire United States	USGS Contour Data
WG	10	Walnut Gulch Experimental Watershed	1:24000 and 1:5000 orthorectified aerial photographs
SRTM	90	North America	Interferometric Synthetic Aperture Radar

5.4. Comparison with Survey Elevations

Dr. Syed collected elevation data in two different regions of Walnut Gulch characterizing different topographic regimes, a highly dissected area in the northeastern portion of the watershed and a hilly region in the southwestern portion of the watershed (Figure 5.2). These contrasting areas provide an opportunity to quantify accuracy of selected digital elevation models in areas that are important from a hydrologic modeling perspective along with areas that are potentially more difficult to represent with topographic models. Ninety elevation points in the highly dissected area of the watershed were collected by a professional surveyor in 1993 and documented in Smiley (1994). Syed (1999) provided a conservative estimate of vertical accuracy for these data of ± 0.2 meters. Thirty-five elevation points were surveyed in the hilly region of the southwestern area of Walnut Gulch by Syed (1999). These data have an average horizontal positional accuracy and vertical accuracy of 0.057 meters and ± 0.16 meters respectively, as quantified by Syed (1999).

For each of the one hundred twenty-five surveyed elevation points, the elevation values were extracted from the corresponding cell for each of the six digital elevation models. The result from this procedure was six elevation values for each surveyed data point from which the mean difference, maximum difference, minimum difference, range of differences, standard deviation of difference, and root mean square error (RMSE) was calculated. These results are presented in Table 5.2 below.

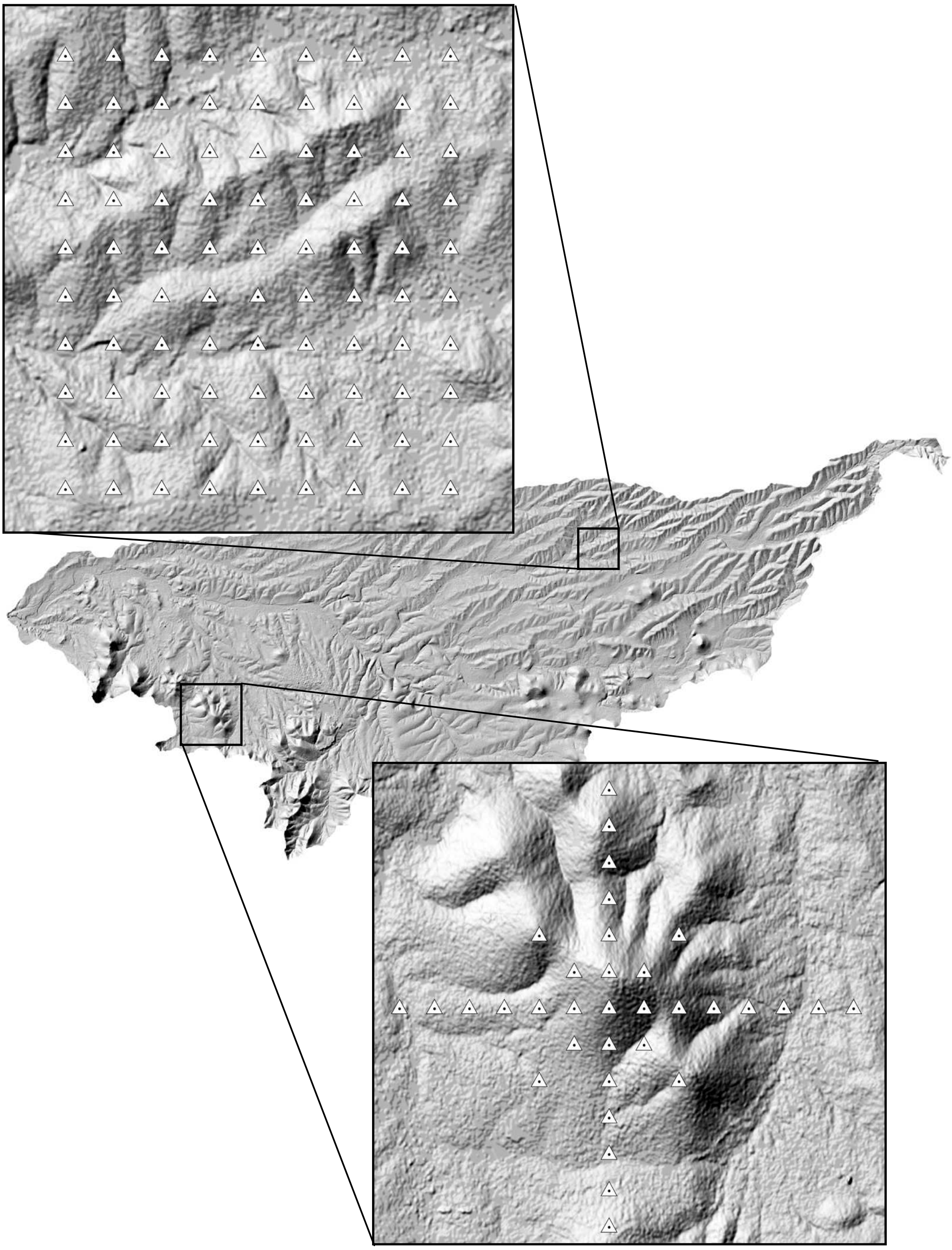


Figure 5.2 Survey locations in Walnut Gulch Experimental Watershed. Highly dissected area data (top) were collected by Smiley (1993) and hilly region (bottom) elevation data were collected by Syed (1999)

The three high-resolution digital elevation models for the Walnut Gulch Experimental Watershed had smaller mean elevation differences compared to the widely available digital elevation models for the highly dissected area of the watershed. However, for the hilly region of the watershed the mean differences for all DEMs in the analysis were approximately the same, with the coarsest resolution DEM performing the poorest. In the highly dissected area, the 2.5-meter Interferometric Synthetic Aperture Radar data were the closest to the survey elevations with a mean of –0.22 meters and a standard deviation of 0.49 meters, and the Walnut Gulch photogrammetric 10-meter digital elevation model had slightly poorer results with a mean of –0.27 meters and a standard deviation of 0.90 meters. As illustrated by the results in Table 5.2 and Figures 5.3 and 5.4, the digital elevation models had lower means and standard deviations for the hilly region compared to the highly dissected area of the watershed. Residuals were computed for the 90 survey points in the highly dissected area and illustrate that the two USGS DEMs (10 meter and 30 meter) and the 90 meter Shuttle Radar Topography Mission (SRTM) DEMS overestimated the elevation values compared to the survey data (Figure 5.3). The mean difference computed by subtracting the survey elevation from the DEM elevation was closer to zero for the hilly region compared to the highly dissected area. The mean elevation difference for the 90 survey locations from the DEM in the highly dissected region was 5.28, 5.37, and 1.90 meters for the USGS 10 meter, USGS 30 meter, and SRTM 90 meter digital elevation models, respectively.

In contrast to the 35 survey points in the hilly region in the southwestern portion of Walnut Gulch, the widely available DEMs had a mean difference of –1.06, -1.08, and 1.06 meters for the USGS 10 meter, USGS 30 meter, and SRTM 90 meter digital elevation models, respectively. Both of the USGS digital elevation models had a smaller standard deviation of elevation difference for the hilly region compared to the highly dissected area of the watershed. However, the ninety-meter shuttle data had a higher standard deviation of elevation difference for the hilly region compared to the highly dissected area.

The residual differences also indicate that the digital elevation models provide a better estimate of topography for the hilly region compared to the highly dissected area. In the highly dissected area, the mean elevation differences for the widely available DEMs were positive, indicating that the DEM elevation values overestimate the surface elevation (Table 5.2 and Figure 5.3). In the hilly region, the mean differences in elevation for the USGS DEMs were slightly negative and therefore underestimate the elevation values. Comparing the distribution of residual values in Figure 5.3 and Figure 5.4, the errors in the hilly region are very close to zero, which also indicated by the values in Table 5.2. For the highly dissected region, both the USGS DEMs and the Shuttle Radar Topography Mission data overestimated elevation values.

Table 5.2 Summary of Results from comparing DEMs with survey data**

Differences between DEMs and survey in hilly southwestern region of Walnut Gulch (N=35)

Statistic	IFSAR 2.5 m	IFSAR 10 m	USGS 10 m	USGS 30 m	WG DEM 10 m	SRTM 30 m	SRTM 90 m
Max	0.78	2.04	1.85	1.45	2.02	xx	25.04
Min	-2.26	-3.93	-3.40	-6.80	-2.83	xx	-13.65
Range	3.04	5.97	5.25	8.25	4.85	xx	38.69
Mean	-1.05	-1.68	-1.06	-1.08	-0.47	xx	1.06
SD	0.69	1.25	1.30	1.56	1.12	xx	7.15
RMSE	1.248	2.088	1.668	1.880	1.200	xx	7.123

Differences between DEMs and survey in dissected northwestern region of Walnut Gulch (N=90)

Statistic	IFSAR 2.5 m	IFSAR 10 m	USGS 10 m	USGS 30 m	WG DEM 10 m	SRTM 30 m	SRTM 90 m
Max	1.04	1.34	13.52	13.32	1.65	xx	10.34
Min	-1.42	-3.76	-0.14	0.26	-2.11	xx	-11.47
Range	2.46	5.10	13.66	13.06	3.76	xx	21.81
Mean	-0.22	-0.72	5.28	5.37	-0.27	xx	1.90
SD	0.49	0.83	2.57	2.48	0.86	xx	3.55
RMSE	0.536	1.094	5.871	5.907	0.896	xx	4.015

** All values are calculated as DEM Elevations – Survey Elevations

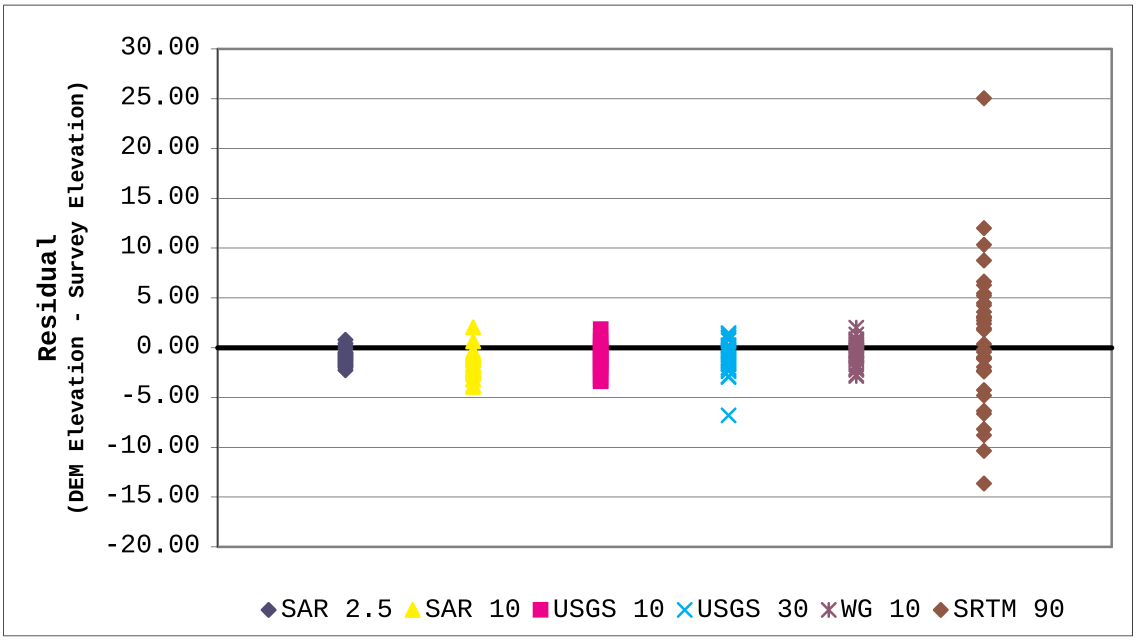


Figure 5.3 Plot of residuals for 35 elevation points in hilly portion of Walnut Gulch

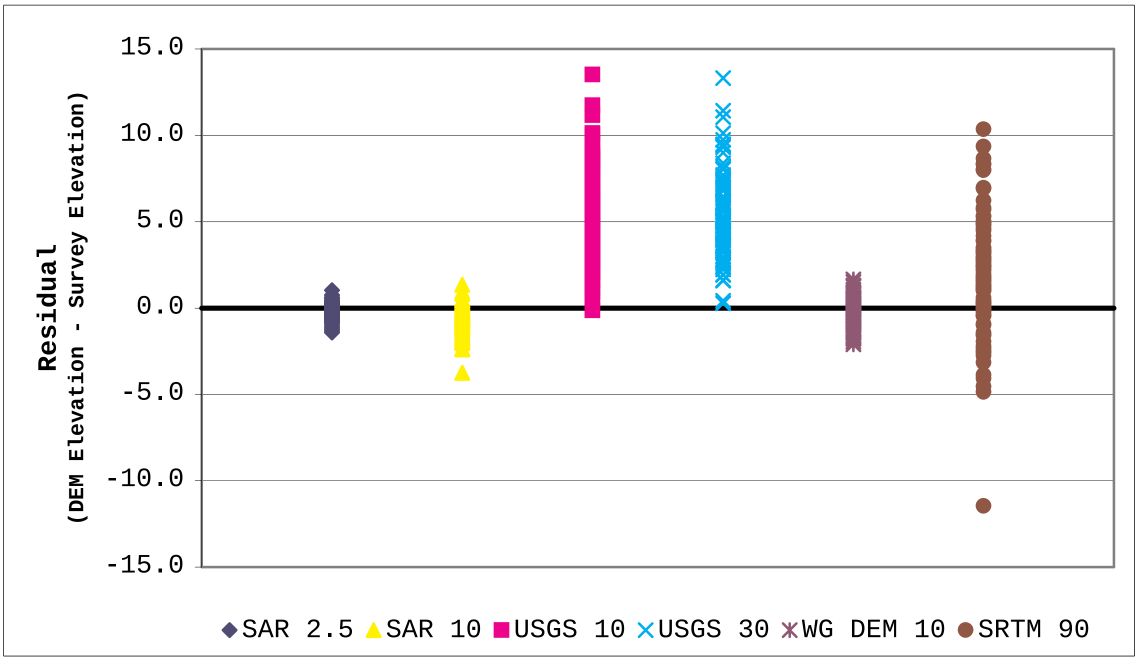


Figure 5.4 Plot of residuals for 90 elevation points in highly dissected portion of Walnut Gulch

A subset of the survey data from the above analysis was selected for the six digital elevations models to examine topographic profiles. Four transects were plotted, two orthogonal transects in the hilly region in the southwestern area of the watershed and two orthogonal transects in the highly dissected area of the watershed. The locations of transects are illustrated in Figure 5.5. For these transects, topographic profiles were extracted from the six DEMs and plotted in Figures 5.6 through 5.9.

For the hilly region in the southwestern portion of the watershed, the two transects plotted in Figure 5.6 and Figure 5.7 indicate that the digital elevation models approximate the surface well. Transect 1 (the north to south transect) has two peaks which are both represented in all of the DEMs examined. Along this transect, the low-lying area between the peaks is not measured with a survey point and therefore cannot be evaluated. Transect 2 (the west to east transect) is also represented well by the six digital elevation models. The single peak in Transect 2 was captured by all six DEMs and the up slope and down slope are estimated reasonably well with the Shuttle Radar Topography Mission 90-meter data that represents the topography the poorest.

The digital elevation models did not perform well in the highly dissected region compared to the hilly region as indicated by Transects 3 and 4. As apparent from both transects, the USGS digital elevation models over estimate the topography in this region while the Shuttle Radar Topography Mission data underestimated the elevation. Transect 4 is particularly interesting because of the entrenched channels near the end of the transect, which are not captured by the three widely available DEMs. The USGS 10 and 30 meter DEMs have slight decreases in elevation near these head cuts but do not represent the incised areas. The SRTM 90 meter data do not capture the tops of the ridge but the elevation values represent the bottoms of the head-cuts.

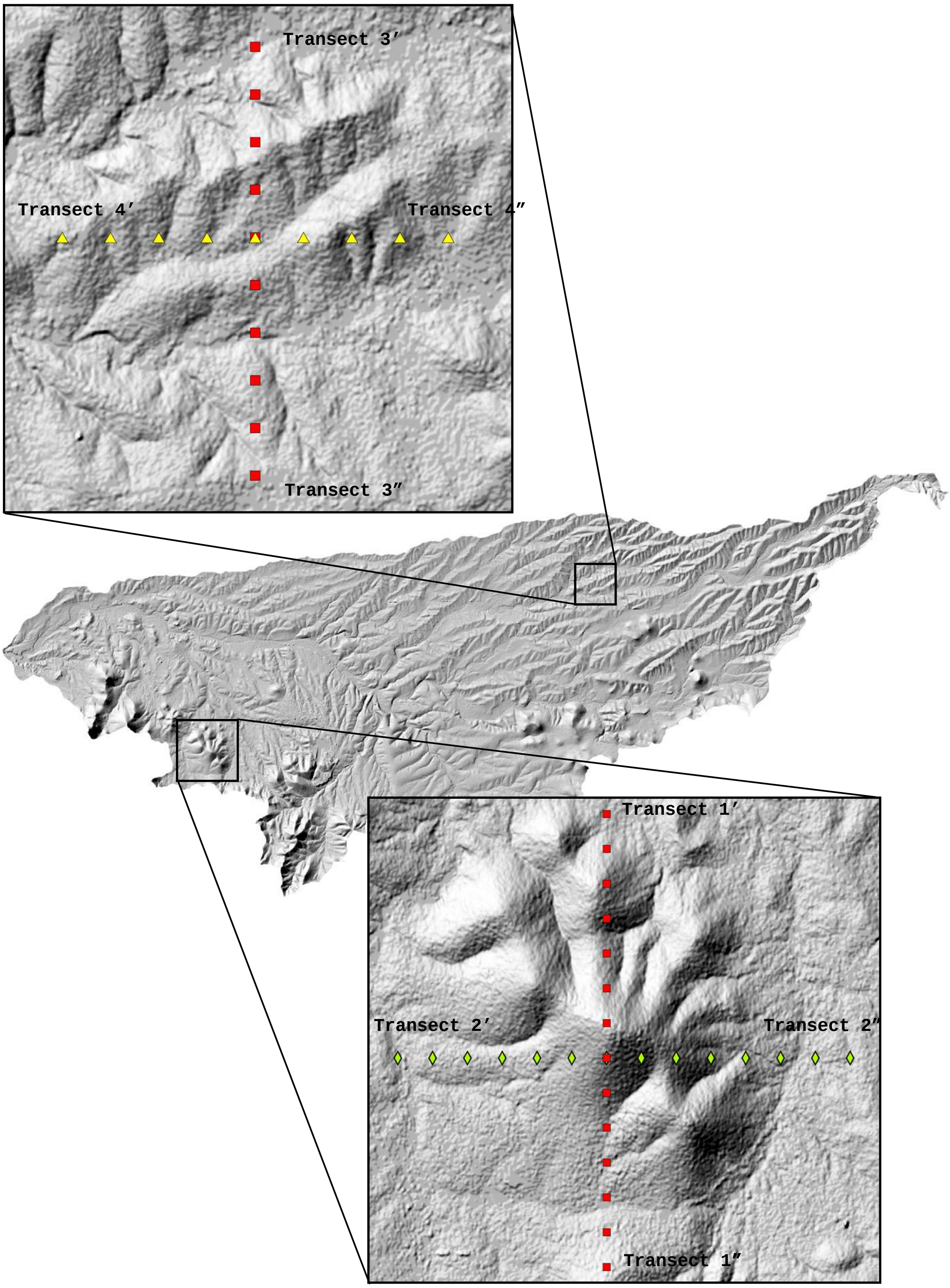


Figure 5.3 Location of survey transects in Walut Gulch

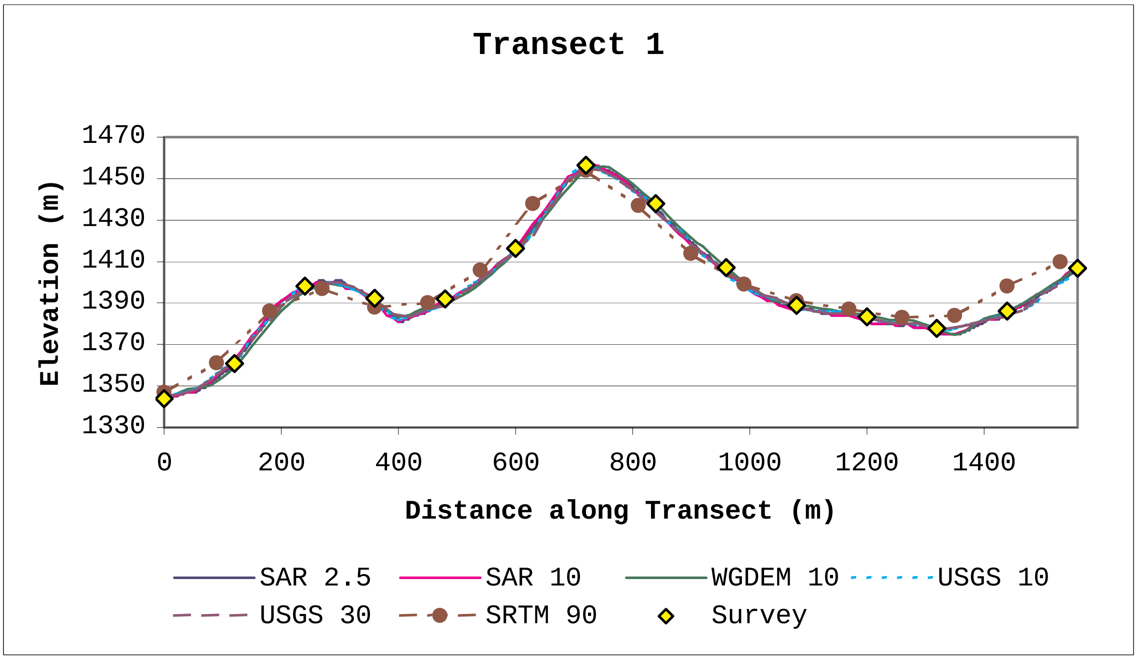


Figure 5.4 North to South transect in hilly region of Walnut Gulch

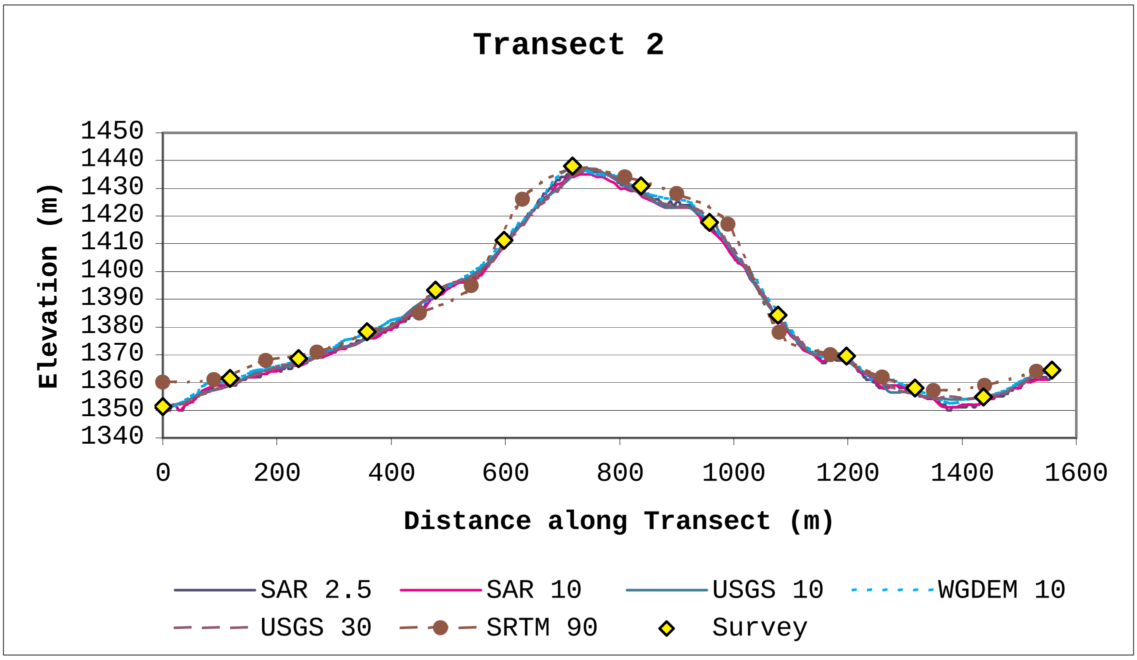


Figure 5.5 West to East transect in hilly region of Walnut Gulch

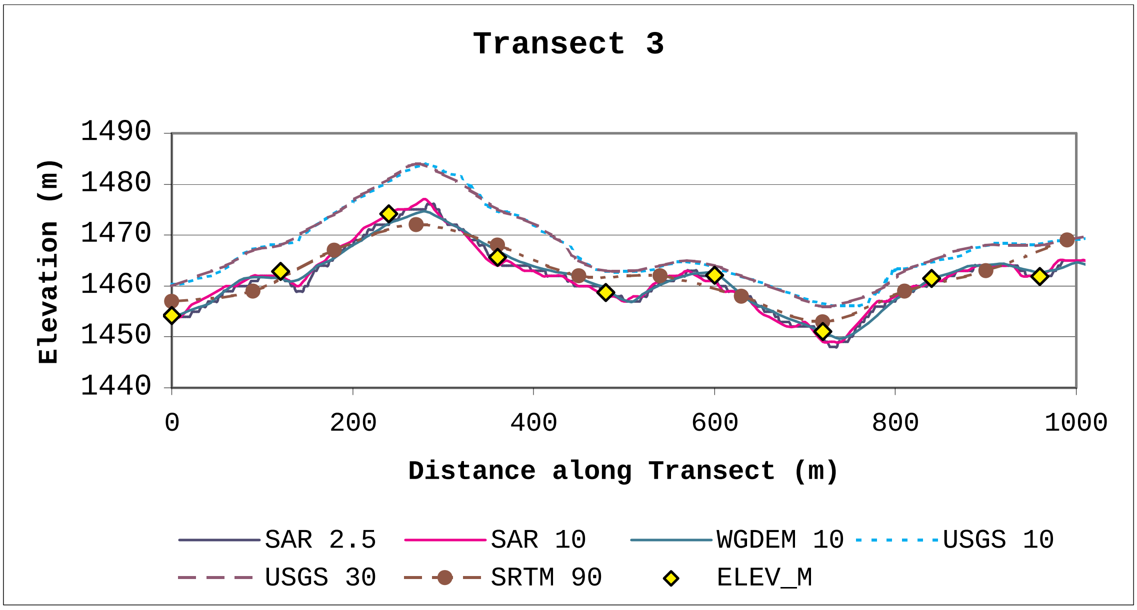


Figure 5.6 North to South transect in the highly dissected area of Walnut Gulch

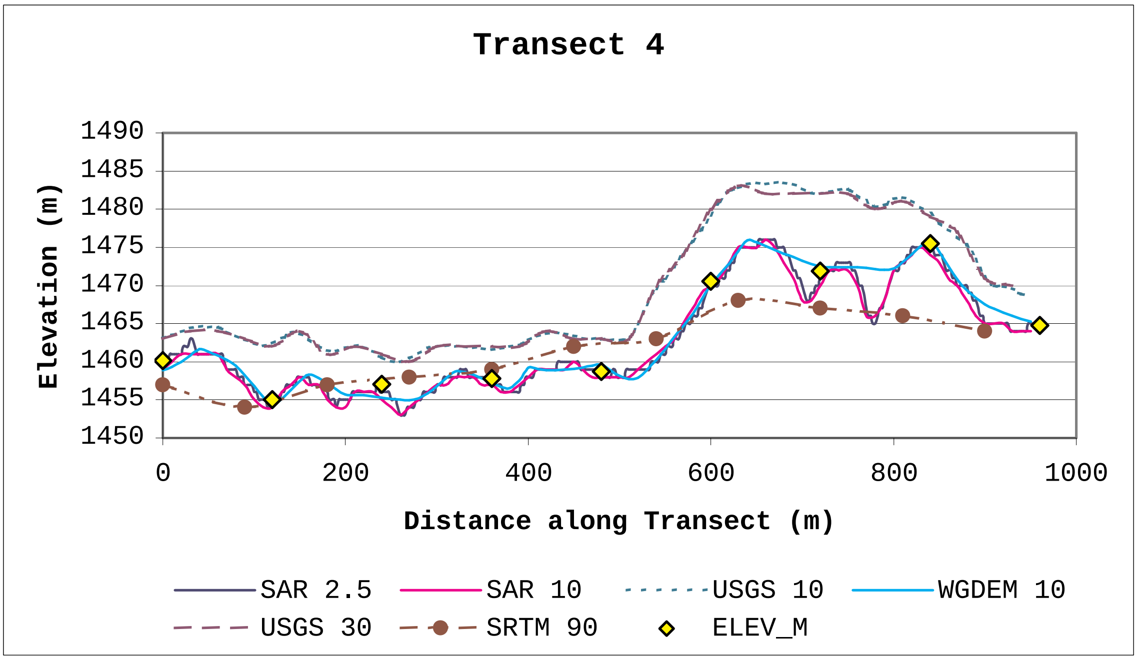


Figure 5.7 West to East transect in the highly dissected area of Walnut Gulch

5.5. DEM Derived Hydrologic Properties

Hydrologic properties are derived from the six digital elevation models and compared in this section. First, the preprocessing steps required to make the DEMs hydrologically correct are discussed. Watershed boundaries are delineated and compared for five different sized watersheds in the Walnut Gulch Experimental Watershed. For the three largest watersheds, the boundaries are subdivided into modeling elements and the hydrologic parameters from the six DEMs are compared.

5.5.1. DEM Preprocessing

Depending on the source and format of the digital elevation models, certain preprocessing steps are required prior to performing the error analysis. As discussed above, the DEMs from the USGS that are distributed as tiles corresponding to 7.5 minute quadrangle maps were mosaiced using the ArcINFO command MERGE. This command combines multiple grids into a single grid, and was performed on the

USGS 30 meter level 2 and USGS 10 meter digital elevation models.

To perform a hydrologic analysis using digital elevation models, the datasets must be what is commonly referred to as “hydrologically correct”. Digital elevation models commonly contain depressional areas or “pits” where water would become trapped and not contribute to a stream channel. These artifacts can be removed using the FILL command in ArcINFO which analyzes the flow paths of the DEM locating these problem areas and modifying the elevation of these cells. An additional step to make a DEM hydrologically correct is to engrave the stream channel into the DEM to ensure that the flow paths coincide with known channels. Since the analysis performed through this research is to evaluate the flow paths using different datasets, this procedure was *not* performed.

5.5.2. Watershed Boundary Delineations

The process of creating watersheds and stream channels requires multiple steps and the creation of intermediary datasets. The first step is to create a flow direction grid which determines the direction water flows out of a given cell. The flow direction algorithm most commonly used and the one used in this analysis is the basic “D8” algorithm which assumes water only flows from a cell in one of eight directions (Farfield and Leymarie, 1991; Martz and Garbrecht, 1998). The cell that water flows out of is assigned a value corresponding to the flow path (Figure 5.10). From the elevation grid, the D8 algorithm assumes water flows along the path of steepest decent and when two flows paths are of equal slope, one is arbitrarily selected. This algorithm typically works well for small watersheds in areas of high relief (Jones, 2002).

32	**64**	**128**
16		**1**
8	**4**	**2**

↘	↓	↓	↓	↙	←
→	↘	↘	↙	↙	↙
↗	↓	↓	↓	↓	←
↓	↓	↙	←	↙	←
↓	↙	←	↙	↙	↙
↙	←	←	←	←	←

2	4	4	4	8	16
1	2	2	8	8	8
128	4	4	4	4	16
4	4	8	16	8	16
4	8	16	8	8	8
8	16	16	16	16	16

Figure 5.8 The numeric value corresponding to the direction water flows out of the center cell (a), flow directions (b), and the corresponding flow direction grid (c).

While the flow direction grid determines how flow moves from an individual digital elevation model cell, the number of cells contributing to a given cell is called the flow accumulation value. The calculation of this grid requires the presence of the flow direction grid with each cell containing a value corresponding to the number of contributing cells. An important characteristic of the flow accumulation grid is the presence of the largest accumulation value at the outlet of the watershed. The flow accumulation grid is also used to locate stream channels within a watershed; cells with a flow accumulation value greater than a user defined threshold are reclassified as stream channels. This user specified reclassification value identifies the initiation of a stream channel and is commonly referred to as the Contributing Source Area (CSA) or critical support area.

In order to perform hydrologic model simulations, watersheds boundaries are delineated and then subdivided into modeling elements that consist of channels and planes. The number of planes and channels or the complexity of the discretization is determined by the contributing source area value. Small CSA values yield a higher number of modeling elements compared to larger CSA values. Determining the most realistic CSA value is site specific (see Syed 1999; Miller 2002). A range of CSA values will be used in this analysis.

From a flow direction grid and a watershed outlet location, a watershed boundary is delineated by identifying all the cells within a DEM that contribute to a watershed outlet. A watershed boundary is delineated for each of the six digital elevation models identified above for five different sized watersheds in the Walnut Gulch Experimental Watershed. Using the same five watershed outlet locations, boundaries are computed and compared below. It should be recognized that due to the differences in resolutions in the DEMs, for each watershed boundary delineated the watershed outlet location was required to be moved a small distance to the point of maximum flow accumulation.

2	4	4	4	8	16
1	2	2	8	8	8
128	4	4	4	4	16
4	4	8	16	8	16
4	8	16	8	8	8
8	16	16	16	16	16

0	0	0	0	1	0
0	4	1	3	0	0
0	0	9	3	2	0
0	1	15	4	4	0
1	19	0	5	0	0
35	12	11	4	2	0

Figure 5.9 A flow direction grid (a) is used to calculate a flow accumulation grid (b).

Watershed boundaries were created for five watersheds in the Walnut Gulch Experimental Watershed using the six digital elevation models. Results from comparing the delineated boundaries to “true” boundaries that were digitized from aerial photographs are presented in Table 5.3. All six digital elevation models under predicted the watershed areas for the two largest watersheds, WG-1 and WG-6. For the largest watershed, the Walnut Gulch DEM predicted the “true” area best followed by the USGS 10 meter DEM with the Shuttle Radar data performing the poorest. For the watershed area draining to flume 6, the USGS 10 meter data were more accurate in estimating area than the other DEMs, with the Shuttle Radar data again performing the worst. The highest resolution data, the boundary delineated with the IFSAR 2.5 meter data was more than 100 hectares (-1.09 percent) under the “true” watershed area. For the smaller watersheds WG-223 and LH-104, the DEMs estimated approximately the same watershed area with the exception of the Shuttle Radar data. As expected, the cell resolution is too coarse for these smaller watersheds and therefore should not be used for simulations at this scale.

For illustrative purposes, the delineated watershed boundaries for watershed LH-104 are presented in Figure 5.11 below. While none of the boundaries calculated from digital elevation models matched the digitized “true” boundary, some did better than others. As expected, the highest resolution IFSAR 2.5 meter DEM appears to be the closest to actual with the coarsest resolution SRTM 90 meter DEM predicting the poorest. For the SRTM DEM, the 90 meter grid size was not detailed enough to represent this small tributary watershed and therefore, the automated boundary delineation routine moved the watershed outlet to the larger stream channel.

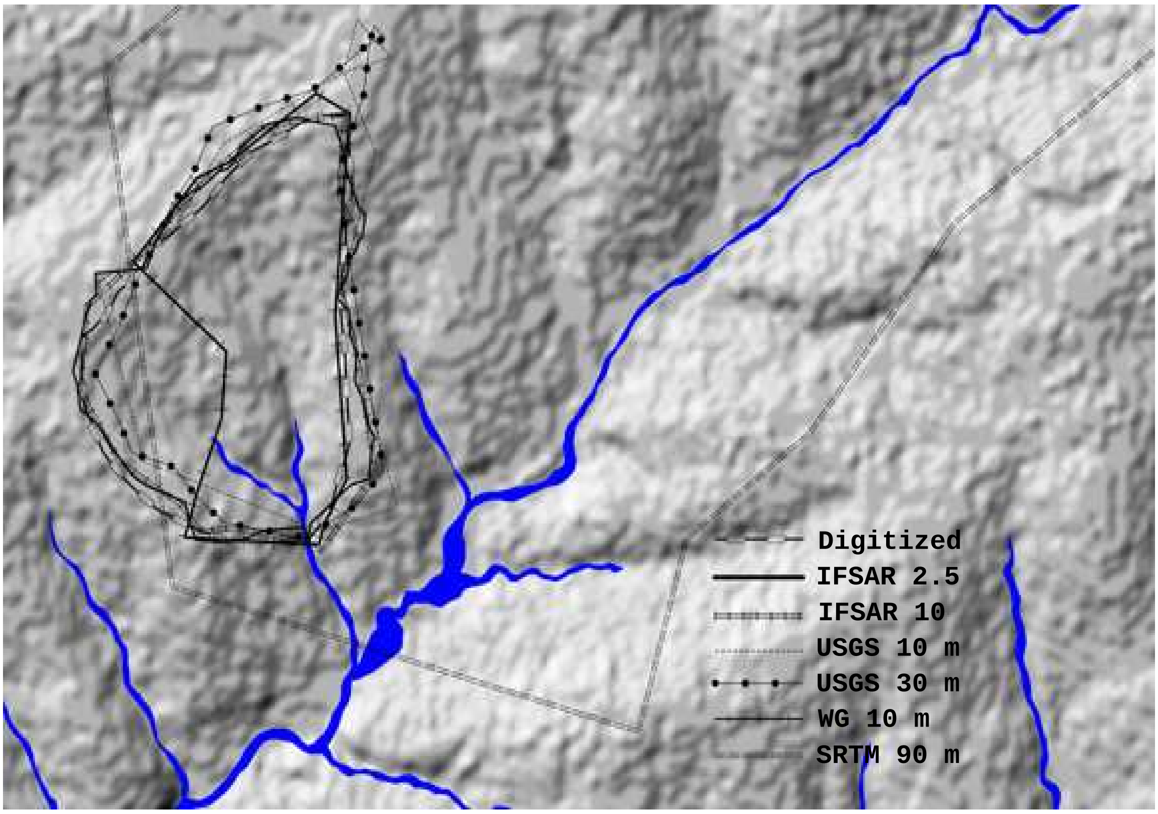


Figure 5.10 Boundaries delineated for Watershed 104 (LH-104) using six digital elevation models

Table 5.3 Area and Perimeter Results from Watershed Boundary Delineation with Six Digital Elevation Models

Watershed	DEM Name	Area (ha)	Difference in Area (ha)	Percent Difference
WG-1	*Digitized*	*14800*	--	--
	SAR 2.5m	14682	-118	-0.80
	SAR 10m	14675	-125	-0.84
	USGS 10m	14709	-91	-0.61
	USGS 30m	14668	-132	-0.89
	WG 10m	14720	-80	-0.54
	SRTM 90m	14191	-609	-4.11
WG-6	*Digitized*	*9353*	--	--
	SAR 2.5m	9251	-102	-1.09
	SAR 10m	9238	-115	-1.23
	USGS 10m	9297	-56	-0.60
	USGS 30m	9283	-70	-0.75
	WG 10m	9305	-48	-0.51
	SRTM 90m	8988	-365	-3.90
WG-11	*Digitized*	*785*	--	--
	SAR 2.5m	781	-4	-0.51
	SAR 10m	784	-1	-0.13
	USGS 10m	783	-2	-0.25
	USGS 30m	788	3	0.38
	WG 10m	792	7	0.89
	SRTM 90m	765	-20	-2.55
WG-223	*Digitized*	*48.35*	--	--
	SAR 2.5m	49.70	1.35	2.79
	SAR 10m	49.92	1.57	3.25
	USGS 10m	50.84	2.49	5.15
	USGS 30m	44.25	-4.10	-8.48
	WG 10m	46.56	-1.79	-3.70
	SRTM 90m	54.08	5.73	11.85
LH-104	*Digitized*	*4.45*	--	--
	SAR 2.5m	4.73	0.28	6.29
	SAR 10m	4.73	0.28	6.29
	USGS 10m	4.75	0.30	6.74
	USGS 30m	4.66	0.21	4.72
	WG 10m	3.28	-1.17	-26.29
	SRTM 90m	53.67	49.22	1106.07

5.5.3. Drainage Dependent Geometric Parameters

To compare the hydrologic parameters derived from different digital elevation models, values will be generated for outlet locations within Walnut Gulch using the six different DEMs. Watershed boundaries will be created using three outlet locations providing a range of watershed sizes from the entire Walnut Gulch Experimental Watershed (14,800 ha) to Watershed 11 (785 ha). These watershed boundaries will then be subdivided using small, medium, and large contributing source area values which correspond to 0.5, 8, and 15 percent of the watershed boundary area, respectively. For each of the watershed boundaries and discretizations, the following values will be calculated providing the comparison of values determined from the different DEMs.

§ Total Watershed Area

§ Number of Channel Segments

§ Mean Channel Length

§ Mean Channel Slope

§ Number of Upland Plane Elements

§ Mean Upland Plane Area

§ Mean Upland Plane Slope

The average slope for the upland planes and channels is measured by computing the slope for the digital elevation model and averaging these values for the element. Computing the slope for the DEM was conducted using ESRI ArcObjects which uses the average maximum technique (Burrough, 1986). This algorithm computes the slope by fitting a plane to the 3 by 3 cell neighborhood surrounding the cell of interest (ESRI, 2003a) and is presented in Equation 5.1.

Equation 5.1 (From ESRI, 2003a)

```
rise_run = SQRT(SQR(dz/dx)+SQR(dz/dy))
degree_slope = ATAN(rise_run) * 57.29578
```

where for the given cell locations:

a	b	c
d	e	f
g	h	i

```
dz/dx = ((a+2d+g) - (c+2f+i)) / (8*x_cell_size)
dz/dy = ((a+2b+c) - (g+2h+i)) / (8*y_cell_size)
```

5.5.4. Watershed Discretization

Three watersheds in the Walnut Gulch Experimental Watershed were used in this analysis, the entire Walnut Gulch boundary (WG-1), Watershed 6 (WG-6), and Watershed 11 (WG-11). Each of these three watersheds was discretized using three different Contributing Source Area (CSA) values, 0.5, 8, and 15 percent of the watershed area. These values were selected using methodology presented by Montgomery and Foufoula-Georgiou (1993) where Syed (1999) plotted the local slope versus area for all pixels in the watershed. However, Syed (1999) noted that “at best, these methods can be used to infer an upper limit on the CSA values” and that “there is as yet no conclusive method for the determination of the contributing source area”.

The hydrologic parameter values estimated from the six digital elevation models for the three largest watersheds, WG-1, WG-6, and WG-11 are presented in Tables 5.3, 5.4, and 5.5, respectively. The largest variability in derived parameter values from the DEMs is in the most complex watershed configuration (0.5% CSA). For the largest watershed (WG-1) with the most complex configuration, the number of channels and planes representing the watershed ranged from a minimum of 96 planes and 224 channels to 107 planes and 259 planes. However, for the largest watershed with the least complex configuration, the number of channels and planes representing the watershed were the same regardless of the DEM. For the smallest watershed (WG-11), the most complex configuration had a range in the number of channels and planes to represent the watershed of 85 to 97 channels and 192 to 237 planes. Due to the small size of the elements of the most complex configuration in relation to the large cell size of the Shuttle Radar data, the most complex configuration could not be completed for WG-11. For the least complex configuration, the number of channels and planes were identical for all digital elevation models.

For a given watershed area and contributing source area value, the hydrologic model parameters vary significantly between digital elevation models. The greatest difference between the mean channel length was 689 meters from watershed 6 (WG-6) for the middle configuration complexity (8%). Watershed 6 (WG-6) discretized at the lowest complexity has the greatest difference between the mean channel slope and mean plane area with differences of 10.51% and 314.4 hectares, respectively. The greatest difference in mean plane slope was 9.07% for the Watershed 11, 8% contributing source area value.

Table 5.4 Discretization data for Walnut Gulch (Flume 1) at different contribution source areas.

§ *CSA = 0.5% (74 ha)*

DEM	Number of Channels	Mean Channel Length (m)	Mean Channel Slope (%)	Number of Planes	Mean Plane Area (ha)	Mean Plane Slope (%)
IFSAR 2.5 m	103	1556.9	9.87	258	56.8	12.36
IFSAR 10 m	101	1564.0	6.69	256	57.2	9.97
USGS 10 m	101	1526.0	4.50	259	56.5	8.99
USGS 30 m	107	1391.9	4.39	259	56.5	8.30
WG DEM 10 m	103	1494.7	6.26	257	57.1	9.84
SRTM 90 m	96	1438.7	2.83	224	63.1	5.37

§ *CSA = 8% (1184 ha)*

DEM	Number of Channels	Mean Channel Length (m)	Mean Channel Slope (%)	Number of Planes	Mean Plane Area (ha)	Mean Plane Slope (%)
IFSAR 2.5 m	9	3921.6	10.12	23	636.6	12.11
IFSAR 10 m	9	3835.9	7.18	23	636.1	10.01
USGS 10 m	9	3845.9	4.29	23	636.5	9.36
USGS 30 m	9	3749.6	3.68	23	636.2	8.27
WG DEM 10 m	9	3927.2	6.29	23	637.7	9.65
SRTM 90 m	9	3335.7	2.45	23	615.3	5.27

§ *CSA = 15% (2220 ha)*

DEM	Number of Channels	Mean Channel Length (m)	Mean Channel Slope (%)	Number of Planes	Mean Plane Area (ha)	Mean Plane Slope (%)
IFSAR 2.5 m	3	6365.9	11.69	8	1830.3	13.67
IFSAR 10 m	3	6207.1	8.35	8	1828.8	11.40
USGS 10 m	3	6357.9	5.71	8	1830.0	10.44
USGS 30 m	3	6248.7	3.64	8	1828.9	9.24
WG DEM 10 m	3	6412.6	7.11	8	1833.3	10.43
SRTM 90 m	3	5937.7	2.85	8	1769.0	5.74

Table 5.5 Discretization data for Watershed 6 (Gage 6) at different contribution source areas.

§ *CSA = 0.5% (16.8 ha)*

DEM	Number of Channels	Mean Channel Length (m)	Mean Channel Slope (%)	Number of Planes	Mean Plane Area (ha)	Mean Plane Slope (%)
IFSAR 2.5 m	96	1309.6	10.67	243	37.9	11.71
IFSAR 10 m	90	1368.9	7.22	234	39.3	9.85
USGS 10 m	90	1314.3	4.44	230	40.2	8.72
USGS 30 m	91	1274.1	4.12	222	41.7	8.44
WG DEM 10 m	101	1189.2	6.44	251	36.9	9.67
SRTM 90 m	96	1119.7	2.88	203	44.0	5.43

§ *CSA = 8% (748.2 ha)*

DEM	Number of Channels	Mean Channel Length (m)	Mean Channel Slope (%)	Number of Planes	Mean Plane Area (ha)	Mean Plane Slope (%)
IFSAR 2.5 m	10	3597.1	10.04	24	384.2	12.27
IFSAR 10 m	9	3888.7	8.25	24	383.3	11.43
USGS 10 m	9	4008.6	4.82	25	369.5	9.53
USGS 30 m	9	3815.7	4.47	23	402.8	8.81
WG DEM 10 m	9	4005.5	7.34	22	420.9	10.93
SRTM 90 m	9	3319.7	2.89	23	389.1	5.54

§ *CSA = 15% (1403.0 ha)*

DEM	Number of Channels	Mean Channel Length (m)	Mean Channel Slope (%)	Number of Planes	Mean Plane Area (ha)	Mean Plane Slope (%)
IFSAR 2.5 m	8	1959.7	12.94	20	9219.6	11.05
IFSAR 10 m	7	2254.7	8.15	19	9199.6	10.43
USGS 10 m	7	2202.1	4.65	18	9237.0	9.50
USGS 30 m	7	2097.8	4.59	18	9264.1	8.56
WG DEM 10 m	7	2267.5	7.42	18	9260.6	10.39
SRTM 90 m	5	2590.6	2.43	13	8949.7	5.55

Table 5.6 Discretization data for Watershed 11 (Gage 11) at different contribution source areas.

§ *CSA = 0.5% (3.9 ha)*

DEM	Number of Channels	Mean Channel Length (m)	Mean Channel Slope (%)	Number of Planes	Mean Plane Area (ha)	Mean Plane Slope (%)
IFSAR 2.5 m	97	282.0	9.69	237	3.3	12.86
IFSAR 10 m	87	311.0	7.31	209	3.7	10.80
USGS 10 m	95	271.7	5.36	229	3.4	8.63
USGS 30 m	88	284.4	5.98	192	4.1	8.30
WG DEM 10 m	85	300.1	6.00	204	3.9	9.34
SRTM 90 m	--	--	--	--	--	--

§ *CSA = 8% (62.8 ha)*

DEM	Number of Channels	Mean Channel Length (m)	Mean Channel Slope (%)	Number of Planes	Mean Plane Area (ha)	Mean Plane Slope (%)
IFSAR 2.5 m	5	2039.33	9.84	13	59.5	14.32
IFSAR 10 m	5	2041.41	6.57	13	59.8	11.81
USGS 10 m	5	1973.46	4.11	13	59.8	9.18
USGS 30 m	5	1910.8	4.15	13	60.3	8.52
WG DEM 10 m	5	1964.99	5.51	13	60.4	10.56
SRTM 90 m	5	1769.82	3.85	13	58.3	5.25

§ *CSA = 15% (117.8 ha)*

DEM	Number of Channels	Mean Channel Length (m)	Mean Channel Slope (%)	Number of Planes	Mean Plane Area (ha)	Mean Plane Slope (%)
IFSAR 2.5 m	5	1532.56	10.09	13	59.5	14.02
IFSAR 10 m	5	1542.18	6.57	13	59.8	11.43
USGS 10 m	5	1489.97	4.06	13	59.8	8.98
USGS 30 m	5	1458.00	4.06	13	60.2	8.30
WG DEM 10 m	5	1478.64	5.46	13	60.5	10.20
SRTM 90 m	5	1287.54	3.35	13	58.4	5.21

5.6. Hydrologic Model Simulations

To evaluate the effects of the different DEM derived hydrologic parameters on simulated runoff, simulations were performed for WG-11 using eleven different rainfall-runoff events, and results were compared with observed data. The discretizations used in the previous sections were modified to capture the unique hydrologic characteristics of WG-11. The watershed contains a pond that retains runoff during rainfall-runoff events. Therefore, this pond contributing area was removed from the total watershed area because this area is assumed to not contribute runoff to the watershed outlet for the events simulated. In addition, the 0.5 percent contributing source area value was replaced with 1.5 percent because of the difficulties in the watershed delineation routines using a small CSA value.

Simulations were performed using the Kinematic Runoff and Erosion model, version 2 (KINEROS2: Smith et al., 1995). KINEROS2 is an event-oriented, physically based model developed for simulating runoff in watersheds where Hortonian overland flow predominates. The model contains mathematical relationships estimating the processes of interception, infiltration, surface runoff, and erosion for small watersheds. KINEROS2 represents the watershed as a cascade of planes and channels where partial differential equations for overland and channel flow, erosion and sediment transport are solved utilizing finite difference techniques. See Appendix C for additional information on KINEROS2.

Model parameters were derived using the Spatial Decision Support System watershed delineation and parameterization routines. Parameters were estimated using readily available land cover and soils GIS datasets and are presented in Appendix G. Land cover parameters were derived from North American Landscape Characterization (NALC) data and soils parameters were derived from NRCS State Soil Geographic (STATSGO) data.

The North American Landscape Characterization (NALC) imagery from 1986 was used because of the temporal distribution of the rainfall events. NALC is land cover data derived from Landsat-MSS satellite scenes and classified into 10 classes specifically for the Upper San Pedro Watershed (Maingi et al., 1999) and is currently available for 1973, 1986, 1992, and 1997. The land cover classes were used to determine interception, roughness, infiltration, and erosion parameters for KINEROS2. WG-11 contains three land cover classes in the 1986 NALC imagery, mesquite woodlands, grasslands, and dessert scrub which consist of 5, 42, and 53 percent of the watershed, respectively.

The STATSGO soils data are created using a compilation of more detailed Soil Survey Geographic (SSURGO) data or from geology, topography, vegetation, and climate along with Land Remote Sensing (LANDSAT) images when SSURGO data are unavailable (USDA, 1994). The soils database contains generalized mapping units where percentages of more detailed classes consisting of soil layers and the depth and soil texture for each layer. These soil texture classes were used to derive the KINEROS2 parameters based on Table 1 of the KINEROS manual (Woolhiser et al., 1990) and the parameters were both depth weighted using the soil characteristics of the top 9 inches of the soil and area weighted using the percentage of each soil sub-class within the generalized class. For this application, due to the relatively small size of WG-11 compared to the size of the generalized soil units, the watershed is contained in one mapping unit. The soil for the watershed is described as 60% gravelly loam, 25% gravel-fine sandy loam, and 15% fine sandy loam. The channel elements were assumed sand which allowed for the simulation of transmission losses along the channel reach.

The rainfall events used in the simulations provide a range of sizes (Table 5.7). The largest rainfall event simulated occurred on August 17, 1986 where approximately 41 millimeters of rain fell over 12 hours, and the smallest event simulated occurred on August 10, 1986 where 7.1 millimeters fell over 4.5 hours. All rainfall and runoff event values were evaluated and documented in Goodrich et al. (1997).

Table 5.7 Rainfall events used in simulations

Rainfall Event Date	Approximate WG 11 rainfall (mm)	Event Duration (min)
25 August 1984	17.9	180
17 July 1985	32.9	360
24 June 1986	18.1	270
15 July 1986	27.9	420
9 August 1986	33.1	270
10 August 1986	7.1	270
14 August 1986	25.3	330
17 August 1986	41.3	720
29 August 1986	32.3	380
3 August 1988	10.6	300
20 August 1988	12.3	360

Simulation output was compared to observed data for the eleven rainfall-runoff events (See Appendix H for all output). The percent error or departure from observed values was calculated for peak runoff and total runoff volume for each event. The average absolute percent error was averaged for each DEM-CSA combination and is presented in tables 5.8 and 5.9. The number of simulations that were greater than or less than the observed values is also presented in tables 5.8 and 5.9. The percent error is calculated as:

$$r = \frac{(predicted - observed)}{observed} \bullet 100$$

where predicted is the KINEROS2 simulated runoff volume or peak flow value, and observed is the measured runoff volume or peak flow value. Negative percent difference values indicate the percentage the simulated value is less than the observed value while positive percent difference values indicate the percentage the simulated value is greater than the observed value. Percent difference values of zero indicated the predicted runoff or peak flow value is equal to the observed value.

Table 5.8 Runoff Volume

DEM	CSA (%)	Average Absolute Percent Error	Number simulations greater/less than observed
SAR 2.5M	1.5	119.2	6/5
SAR 2.5M	8.0	90.0	3/8
SAR 2.5M	15.0	85.9	3/8
SAR 10M	1.5	108.6	4/7
SAR 10M	8.0	85.8	3/8
SAR 10M	15.0	81.0	2/9
USGS 10M	1.5	104.4	4/7
USGS 10M	8.0	80.9	2/9
USGS 10M	15.0	79.4	2/9
USGS 30M	1.5	106.9	3/8
USGS 30M	8.0	80.4	2/9
USGS 30M	15.0	78.5	2/9
WG 10M	1.5	106.6	4/7
WG 10M	8.0	84.3	3/8
WG 10M	15.0	81.0	2/9
SRTM 90M	8.0	77.9	2/9
SRTM 90M	15.0	74.7	2/9

Table 5.9 Peak Runoff

DEM	CSA (%)	Average Absolute Percent Error	Number simulations greater/less than observed
SAR 2.5M	1.5	81.0	5/6
SAR 2.5M	8.0	63.6	3/8
SAR 2.5M	15.0	64.1	2/9
SAR 10M	1.5	96.4	4/7
SAR 10M	8.0	66.2	3/8
SAR 10M	15.0	62.6	1/10
USGS 10M	1.5	78.9	3/8
USGS 10M	8.0	67.1	1/10
USGS 10M	15.0	70.5	0/11
USGS 30M	1.5	82.6	5/6
USGS 30M	8.0	67.6	1/10
USGS 30M	15.0	72.3	0/11
WG 10M	1.5	80.0	4/7
WG 10M	8.0	63.4	2/9
WG 10M	15.0	65.8	1/10
SRTM 90M	8.0	69.9	1/10
SRTM 90M	15.0	76.0	0/11

In general, using the uncalibrated model parameter values from look-up tables did not produce simulated runoff volumes or peak flow values that were close to observed values. Comparing the runoff volume values, the average absolute percent error ranged from a low of 74 percent for the SRTM 90 meter DEM – 15 percent CSA simulation to 119 percent for the SAR 2.5 meter DEM – 1.5 percent CSA simulation. Simulated runoff volumes under predicted the observed runoff volume for almost 75 percent of the simulations (138 of 187 simulations).

The predictions were slightly better for the peak runoff values; however, predictions were still poor. The average absolute percent error for peak runoff predictions ranged from a low of 62.9 percent for the SAR 10 meter 15 percent CSA value simulation to 96.4 percent for the for the SAR 10 meter 1.5 percent CSA value. Simulated peak runoff also under predicted observed peak runoff for almost 81 percent of the simulations (151 of 187 simulations).

Scatter plots of simulated versus observed runoff volumes and peak runoff values for the different digital elevation models and contributing source area values are presented in Figures 5.11 and 5.12. For the majority of events, the runoff volumes and peak flow values increased with decreasing CSA values. This is counter intuitive to the changes in average slope values presented in Table 5.6 where slopes slightly increased with increasing CSA values. However, the total channel lengths increase drastically with decreasing CSA values indicating that the channel processes dominate, produce lower upland losses from interception and infiltration, and higher subsequent runoff volumes and peak flows.

For the largest runoff event, all DEMs with the 1.5 percent CSA performed simulations that were the closest to observed values. The SAR 2.5 meter DEM, SAR 10 meter, and USGS 30 meter DEM predicted runoff volumes the closest with percent error value of 0.1, -8.9, and –10.2, respectively. The USGS 30 meter DEM, the SAR 10 meter DEM, and the Walnut Gulch 10 meter DEM predicted peak runoff values the closest with percent error values of 0.9, -1.2, and –2.5, respectively.

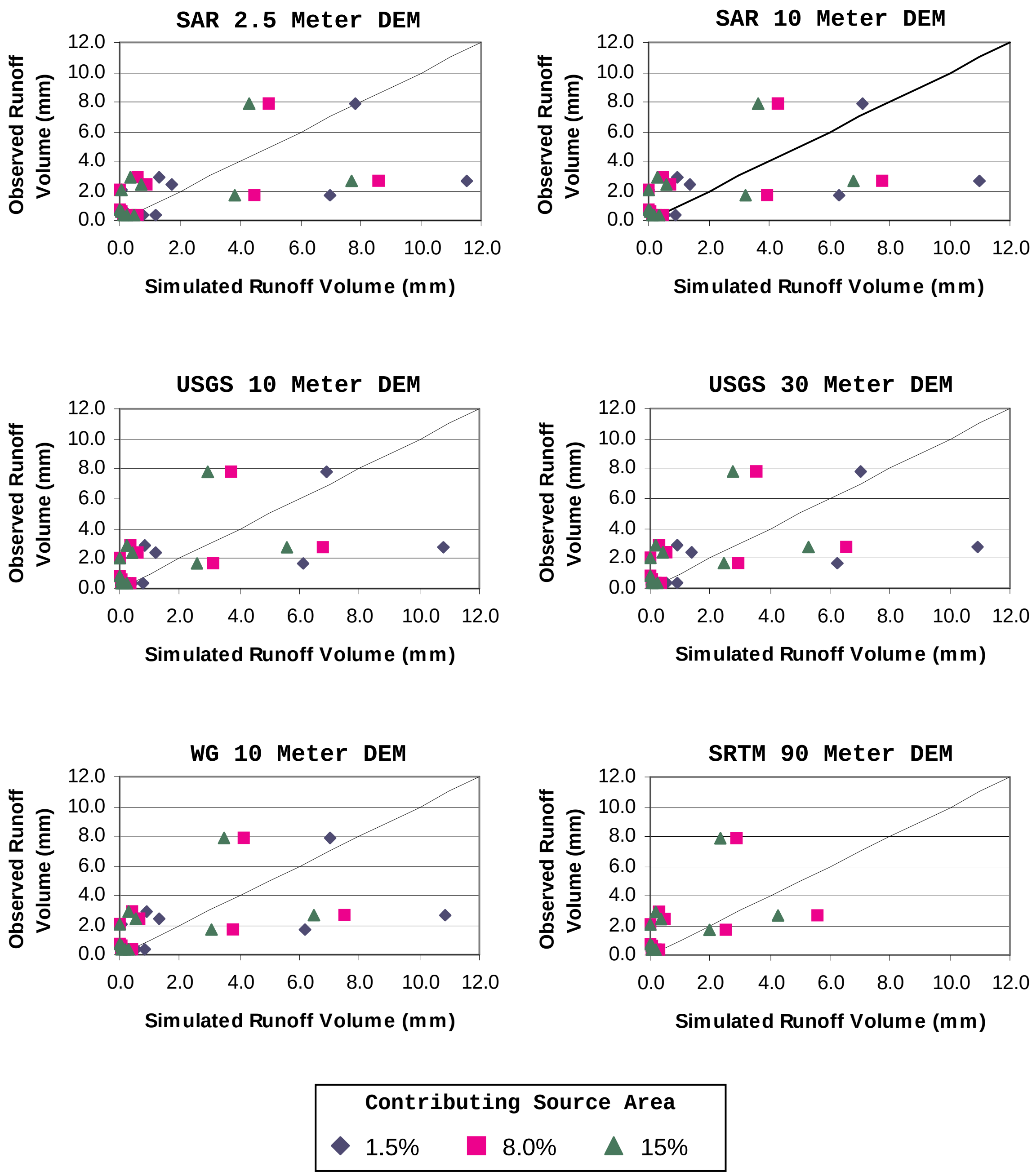


Figure 5.11 Scatter plots of observed versus simulated runoff volumes for different digital elevation models and contributing source area values for Watershed 11

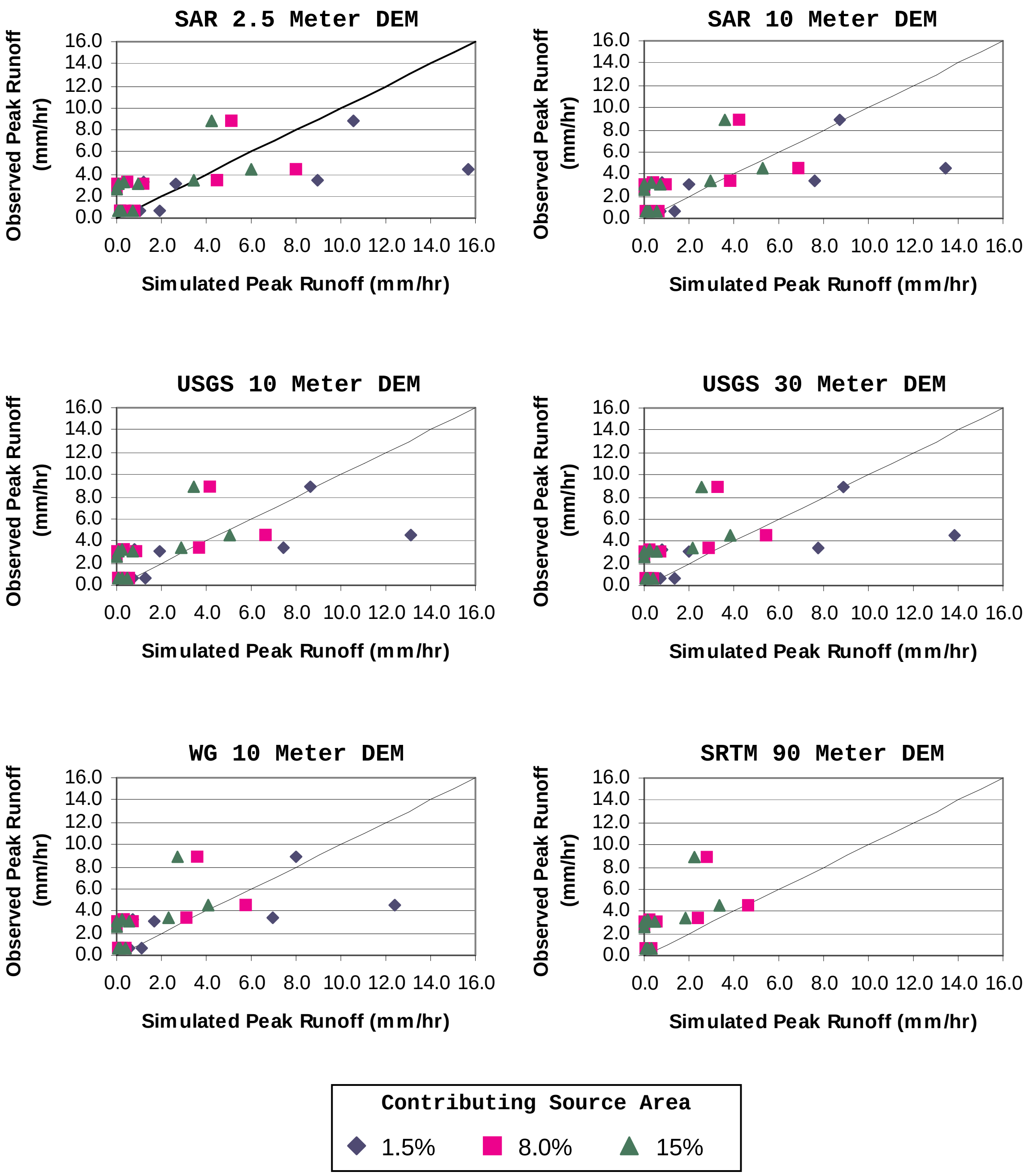


Figure 5.12 Scatter plots of observed versus simulated peak runoff for different digital elevation models and contributing source area values for Watershed 11

5.7. Summary and Conclusion

After examining the range in model parameter values derived from digital elevation models, the selection of DEM to include in the model parameterization process will definitely affect the simulation modeling results. Given the selection of available DEMs to perform modeling tasks, which DEM will produce the best results? Comparisons conducted with the survey data indicate the IFSAR 2.5 meter data are the most accurate. However, the modeling results for Watershed 11 did not coincide with the error analysis; the IFSAR 2.5 meter DEM did not produce simulation results that were more accurate that the other DEMs. For the eleven rainfall-runoff event, all DEM-CSA combinations produced poor results. Based on the large differences between simulated and observed values, soil and land cover derived parameters should be reexamined prior to making conclusive statements about the “best” the digital elevation model – contributing source area values for WG-11.

CHAPTER 6

EVALUATION OF THE SENSITIVITY OF MANAGEMENT SYSTEM RANKINGS BY THE SDSS

6.1. Introduction

After examining the changes in hydrologic modeling parameter values derived from the six digital elevation models, Chapter 6 evaluates the sensitivity of the management systems rankings by the spatial decision support system based on the different digital elevation models, contributing source areas, and precipitation event sizes. As illustrated in Chapter 5, different DEMs and CSA values produce different topographic parameter values and therefore hydrologic simulation results using different DEMs are expected to be unique. However, the purpose of this analysis is to evaluate the effect of differences in DEMs, CSA values, and precipitation event sizes on management system rankings by the decision support system. Specifically, do the ordinal rankings of management system alternatives change as a function of the digital elevation model, contributing source area value, and precipitation event size used in the simulation?

6.2. Methods

The simulations and analysis for this study are performed on Watershed 11 in the Walnut Gulch Experimental Watershed (Figure 5.1). This watershed was selected because of its relatively small size and subsequent sensitivity to changes in management. During the winter of 2003, fence locations were recorded with hand-held global positioning system units and pasture boundaries were mapped providing estimates of the location and size of pastures.

Six management systems were created to evaluate the sensitivity of the digital elevation models, contributing source area, and precipitation event size on spatial decision support system rankings (Figure 6.1). The management systems contain pasture boundaries derived from field surveys with water sources moved to different locations within each pasture to control the distribution of livestock. Managements System 1 has water locations clustered in the southeast portion of the watershed. Management System 2 has water sources for each pasture located outside the watershed boundary, but the livestock distribution will still affect modeling results. Management System 3 uses real world pond locations as natural water sources. Pond locations were obtained from spatial data developed by the USDA Agricultural Research Service, Southwest Watershed Research Center. The fourth, fifth, and sixth management systems vary the water source locations to different places within the three pastures. Management System 4 has two water points located outside the watershed boundary, while Management System 5 has one water point located outside of the watershed boundary. For the pasture that covers the majority of Watershed 11, Management System 6 has the water point the furthest away from the watershed boundary.

The modeling procedure was comprised of multiple steps and is depicted graphically in Figures 6.2 and 6.3. The first step was to subdivide the 785-hectare watershed boundary into watershed elements. Contributing source area values of 1.5 percent (11.8 ha), 8 percent (62.8 ha), and 15 percent (117.8 ha) of the watershed area were selected so that results from this analysis could be evaluated within the context of results presented in Chapter 5. Because errors were produced during watershed delineations for the SRTM 90 meter data using the 0.5 percent CSA value, the smallest CSA value was increased to 1.5 percent for the simulations. However, this increase in CSA did not yield successful delineations and therefore, simulations were not performed for the 1.5 percent CSA value - SRTM 90 meter DEM combinations. These ranges in CSA values allow the sensitivity of CSA on sediment yield to be evaluated.

For each management system and each subdivision from the different digital elevation models, parameters affected by livestock impact were modified using RANGEMAP (Guertin et al., 1998) routines incorporated in the spatial decision support system (See Section 4.3.2 above). These modified parameters were simulated using KINEROS with six different precipitation events: a 5 year - 30 minute event, a 5 year - 60 minute event, a 10 year - 30 minute event, a 10 year - 60 minute event, a 100 year - 30 minute event, and a 100 year - 60 minute event (Figure 6.4). While it is recognized that rainfall events in the semi-arid southwest exhibit a high degree of spatial variability (Osborn et al., 1993), for this analysis, rainfall was assumed spatially uniform. This assumption prevents complicating interactions between livestock distribution and rainfall distribution during simulations. For example, management systems with a high concentration of livestock impacts in an area that receives a more intense rainfall would produce higher rates of erosion compared to a different management system that has an equally high concentration of livestock impact in an area that receives a less intense rainfall.

The different combinations of 6 DEMs, 3 CSA values, 6 management systems, and 6 precipitation event sizes yield 648 simulations. However, as stated above, the watershed delineations with the smallest CSA value (1.5 percent) produced errors using the Shuttle Radar Topography Mission 90 meter data. These errors result from the large cell size relative to the small contributing source area. This relationship results in poorly defined water flow paths which produce errors in the watershed delineation process. As a result, the combinations of DEMs, CSA value, management systems, and precipitation events yielded 612 simulations that will be used in this analysis.

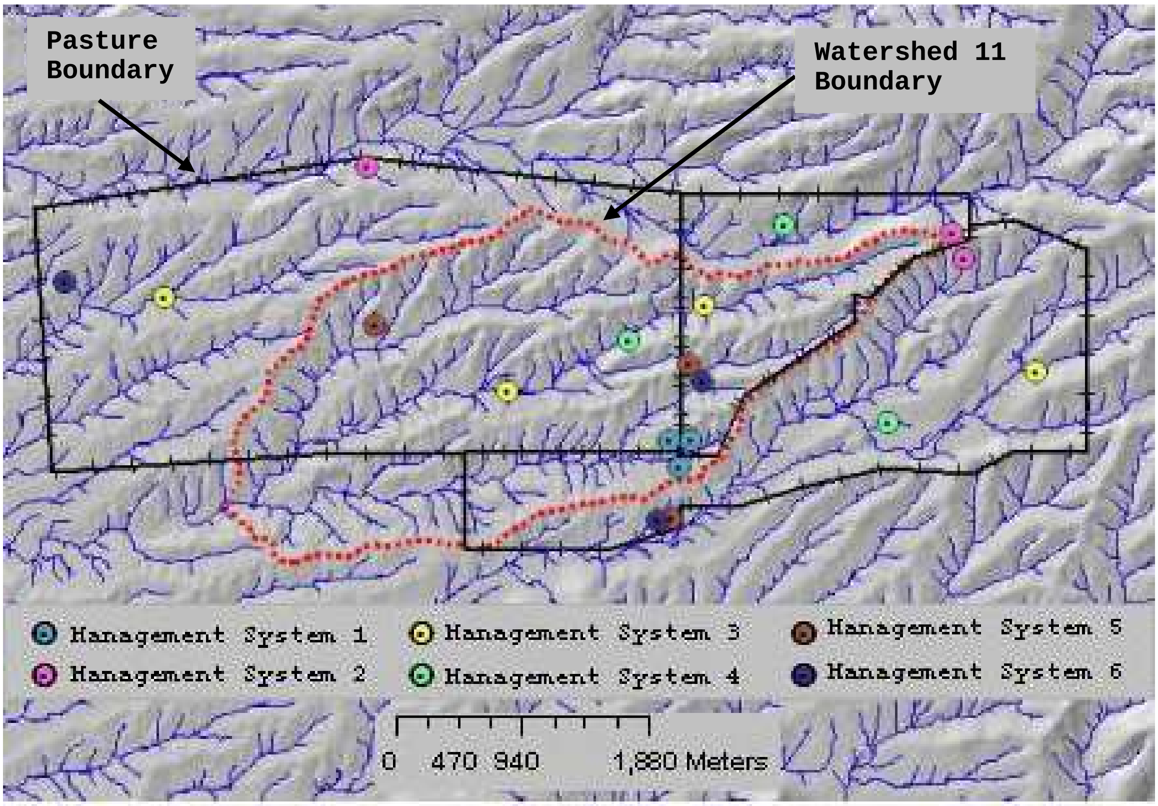


Figure 6.1 Management Systems used to evaluate the impact of digital elevation model uncertainty on the spatial decision support system ranking of alternatives.

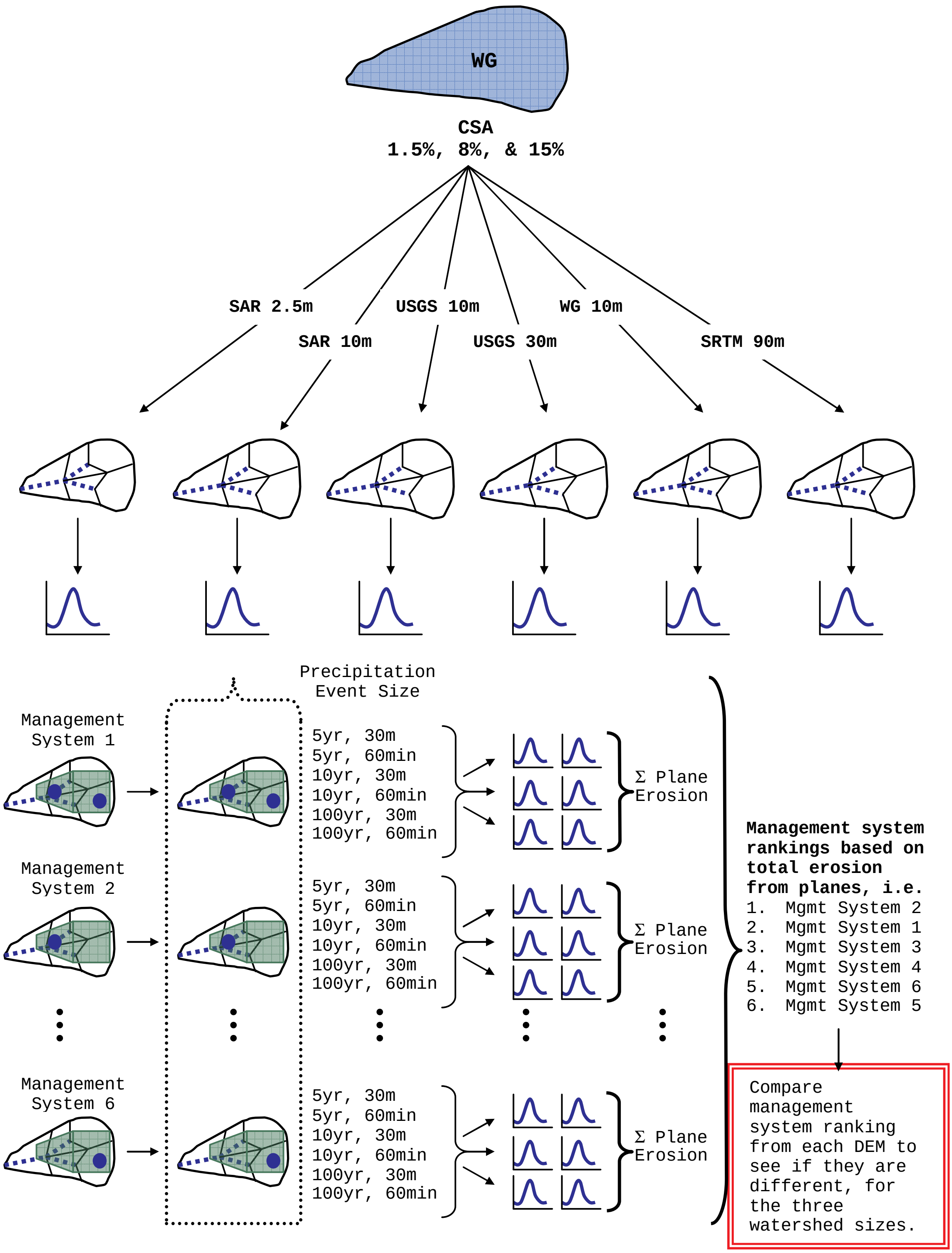
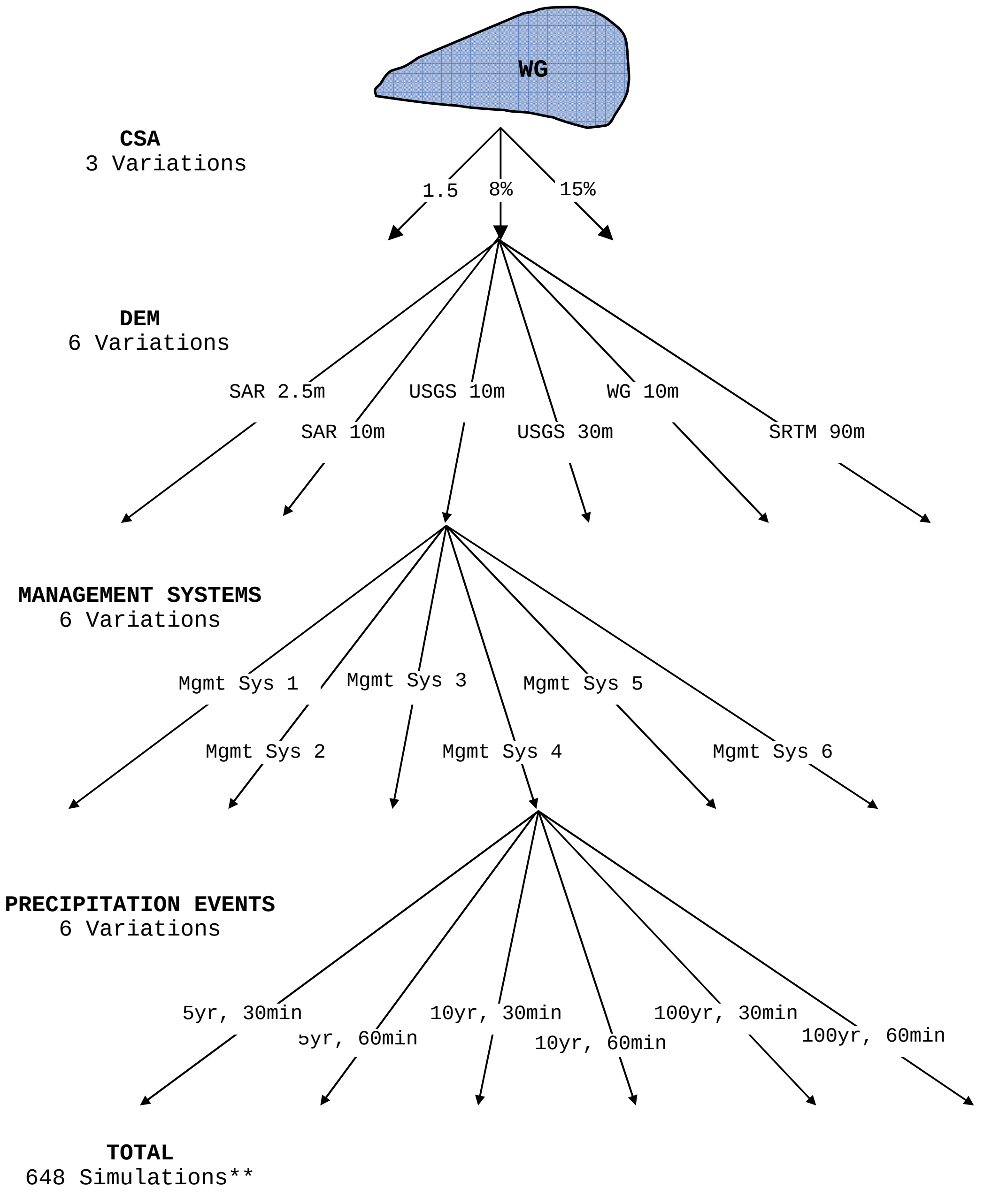


Figure 6.2 Procedure to compare ranking of management system alternatives using different digital elevation models in the spatial decision supports system.



** Actually had 612 simulations because of errors in discretizing watershed for CSA of 1.5% with SRTM 90 meter DEM

Figure 6.3 Different combinations of simulations performed by the Spatial Decision Support System.

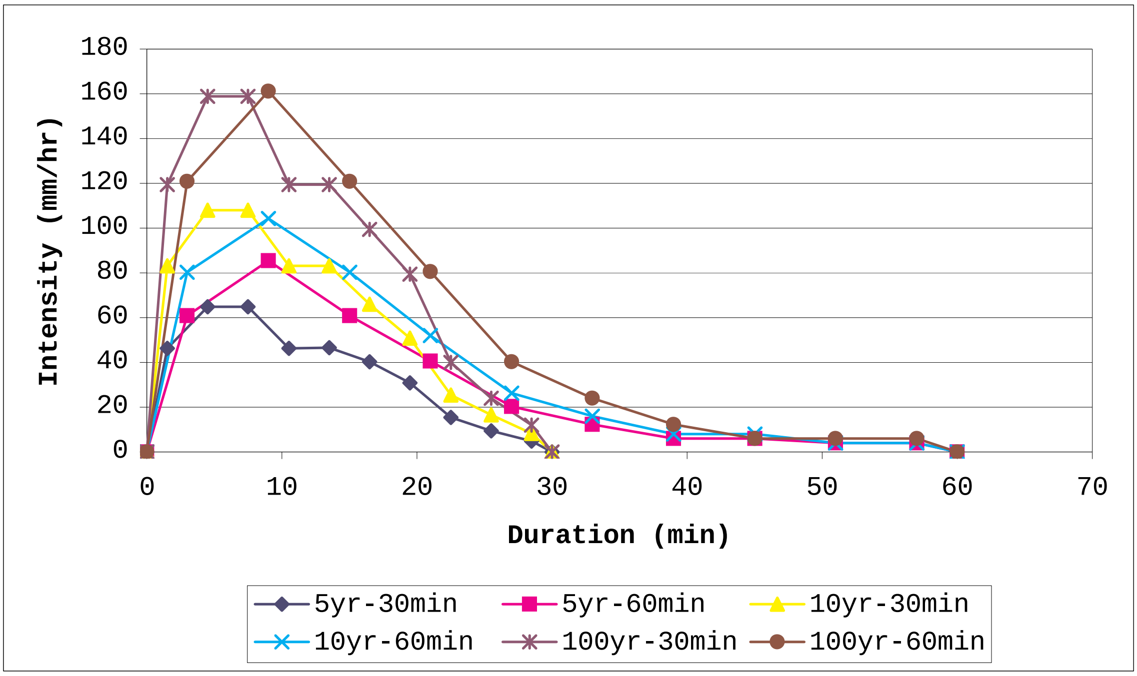


Figure 6.4 Design storms used in simulations

6.3. Results

The grazing intensities for the six management systems are depicted in Figure 6.5. These figures illustrate the grazing intensity and subsequent impact on soil hydraulic properties of the distribution of livestock within a pasture. Grazing intensities are a function of the location of a water point in a pasture because only the location and number of water points changed between the management systems.

Individual simulation results are organized to view sediment yield values and management system rankings for the different DEMs while varying the contributing source area values (1.5 percent, 8.0 percent, and 15 percent) and rainfall event sizes (5-year 30-minute, 5-year 60-minute, 10-year 30-minute, 10-year 60-minute, 100-year 30-minute, and 100-year 60-minute). Management systems are ranked based on the sediment yield produced for the simulations. An objective in designing rangeland management systems is to reduce sediment yield. As a result, the “best” management system is the system that has the lowest sediment yield predicted by KINEROS, and the “worst”

Figure 6.5 Grazing intensity for Management Systems (Darker areas indicate higher grazing intensity)

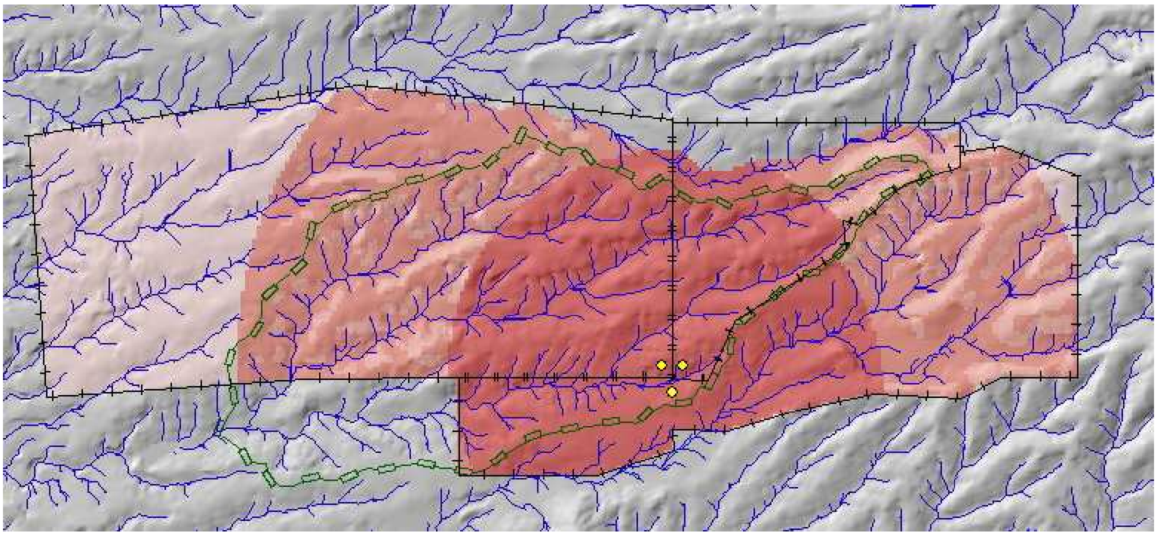


Figure 6.5(a). Grazing intensity for Management System 1

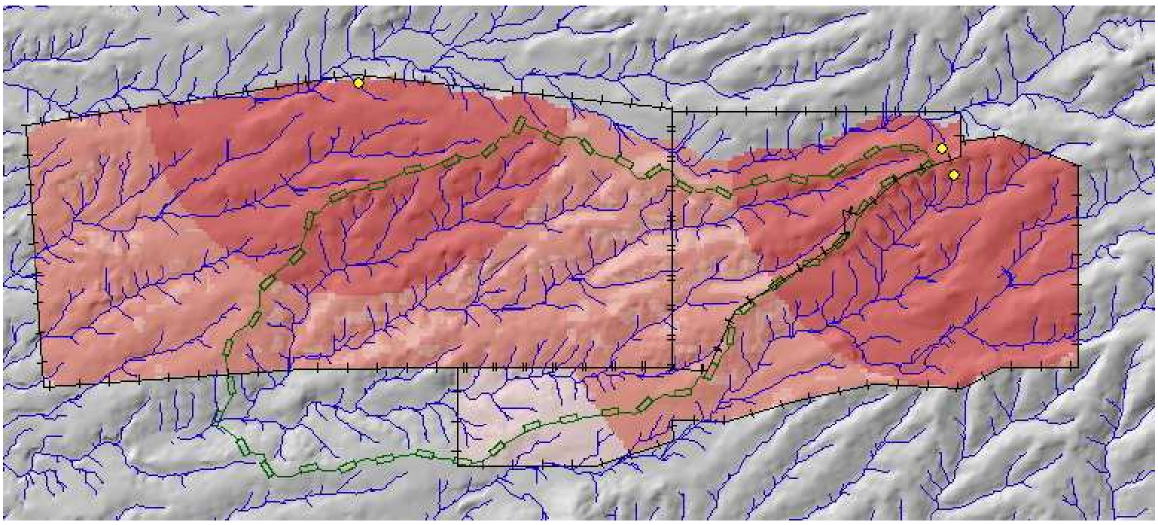


Figure 6.5(b). Grazing intensity for Management System 2

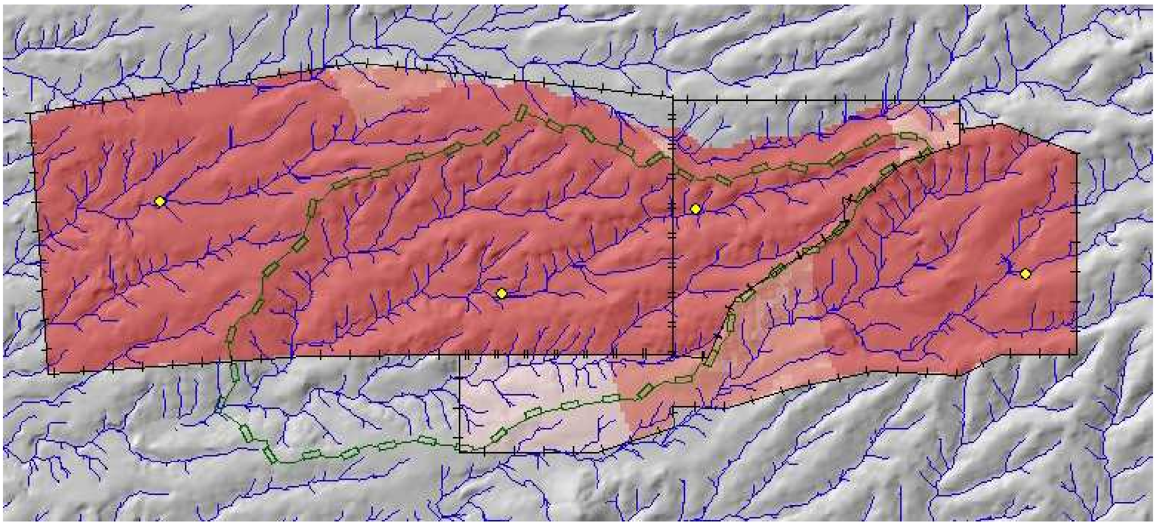


Figure 6.5(c). Grazing intensity for Management System 3

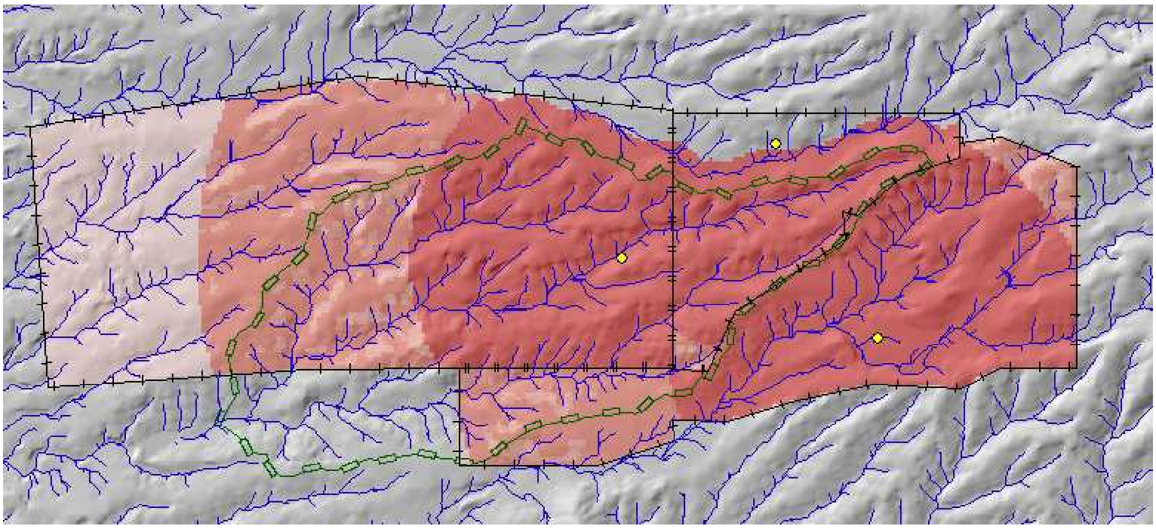


Figure 6.5(d). Grazing intensity for Management System 4

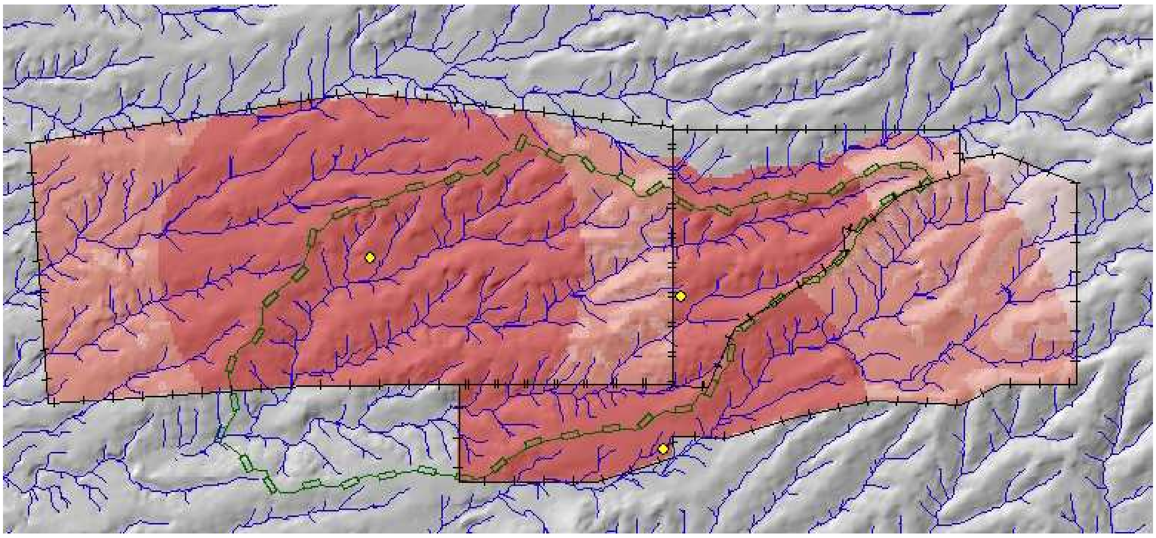


Figure 6.5(e). Grazing intensity for Management System 5

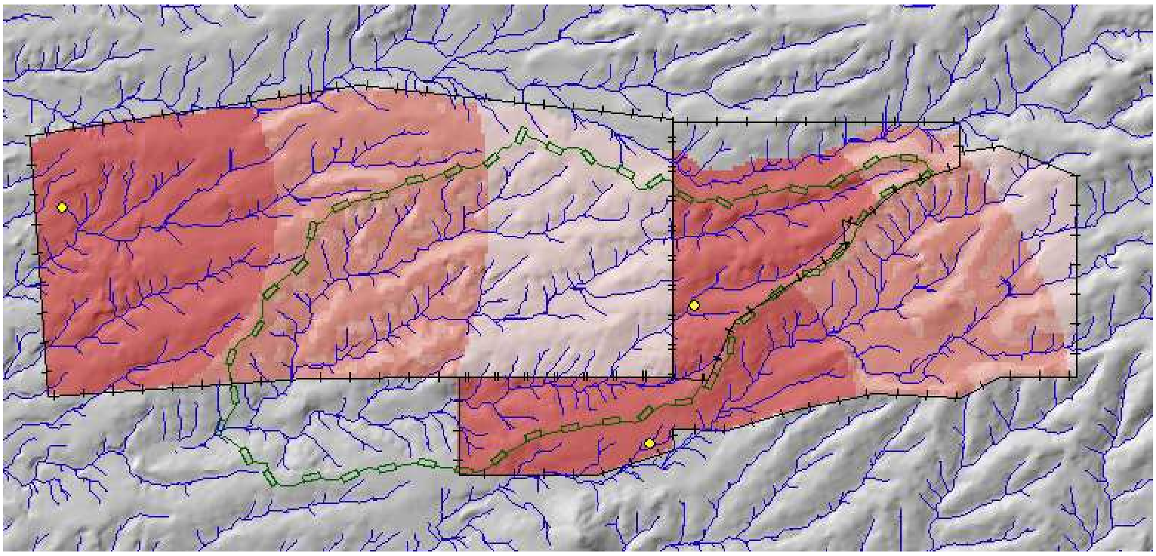


Figure 6.5(f). Grazing intensity for Management System 6

management system is the system that has the highest sediment yield predicted by KINEROS. Simulations for the six precipitation events using a 1.5, 8.0, and 15 percent contributing source area values are presented in Appendix I, Tables I.1 – I.6, Tables I.7 – I.12, and Table I.13-I.18, respectively.

Simulations using the IFSAR 2.5 meter DEM produced higher sediment yield values compared to sediment yield results from simulations using the five other DEMs. Using the 8 percent CSA, 5-year, 30-minute precipitation event with Management System 6 as an example (Table F.7), simulations using the IFSAR 2.5 meter DEM produces sediment yield values that were over 3 times higher than sediment yield values from simulations using the IFSAR 10 meter DEM, 6.8 times higher than sediment yield values from simulations using the Walnut Gulch 10 meter DEM, 14.4 times higher than sediment yield values from simulations using the USGS 30 meter DEM, 19 times higher than sediment yield values from simulations using the USGS 10 meter DEM, and 28.5 times higher than sediment yield values from simulations using the SRTM 90 meter DEM. This relative pattern was expected based on the slope values determined in the analysis performed in Chapter 5. Also expected was that simulations based on the Shuttle Radar Topography Mission 90 meter data produced the lowest sediment yield values, coinciding with the lower slope values determined from the analysis conducted in Chapter 5.

The relative differences among sediment yield values are greater for smaller precipitation event sizes compared to larger precipitation event sizes. Comparing simulation results from smallest and largest precipitation events (5 year, 30 minute simulation and the 100 year, 60 minute simulation) using Management System 1 with an 8 percent contributing source area as an example, sediment yield was 3.1 times higher and 7.4 times higher for simulations with the IFSAR 2.5 meter DEM than the IFSAR 10 meter DEM, respectively. A similar pattern was exhibited by simulations with the 15 percent contributing source area for Management System 1; sediment yield was 1.5 times higher for simulations using IFSAR 2.5 meter DEM than for simulations using IFSAR 10 meter DEM for the 5 year, 30 minute precipitation event, and 4.4 times greater for the 100 year, 60 minute precipitation event.

Excluding sediment yield results from simulations using the Shuttle Radar Topography Mission 90 meter DEM, as the contributing source area increases the sediment yield decreases. For a given DEM, management system, and rainfall event size, the smallest CSA (1.5 percent) produced the highest sediment yield of the three CSA values for all but seven simulations, and never had the lowest sediment yield estimate of the three CSA values. The largest CSA value (15 percent) produced the lowest sediment yield in 105 of the 180 simulations, and produced the highest of the three sediment yield estimates in 5 of the simulations. The middle CSA value (8 percent) had the middle of the three sediment yield estimates during 103 of the 180 simulations and the lowest of the three sediment yield estimates for 75 of the simulations.

A frequency analysis was performed to examine the management system rankings. Simulation results were grouped based on the modeling variable of interest (i.e. DEM, CSA, or precipitation event size). For each grouping, the number of occurrences each management system was ranked first through six was calculated and plotted (Tables 6.1 through 6.13). This analysis provides insight into the changes in distribution of the management system rankings based on different DEMs, contributing source area values, and precipitation events sizes. Management systems were ranked based on minimizing erosion; the highest ranked or “best” management system produced the lowest sediment yield. Conversely, the lowest ranked or “worst” management system produced the highest sediment yield.

The management system rankings for all simulations are illustrated in Table 6.1. Management System 6 was ranked the best during half (50 percent) of the 612 simulations compared to Management System 1 and 2, which were ranked the best during 14.7 percent of the simulations. Management Systems 4 and 3 were ranked best the fewest during 4.9 and 2.0 percent of the simulations, respectively. Examining the management systems that were ranked the lowest, Management System 3, Management System 4, and Management System 5 were ranked sixth for 35.3, 21.6, and 17.6 percent of the simulations, respectively. Management System 2 ranked the lowest the least frequently (7.8 percent of the simulations) while Management Systems 1, and 6 ranked the lowest for 8.8 percent of the simulations.

The frequency of management system rankings from simulations using a 1.5 percent, 8.0 percent, and 15 percent contributing source area value are in Tables 6.2, 6.3, 6.4. For simulations with the smallest contributing source area (1.5 percent), Management System 6 was ranked the best in 60 percent of the simulations while Management System 3 was never ranked the best (0 percent). The frequency of management systems ranked 2 through 6 is not as consistent compared to ranking 1. For example, Management System 3 was ranked third for 23 percent of the simulations while Management Systems 1, 2, and 4 were ranked third for 20 percent of the simulations.

Unlike the rankings of the 1.5 percent contributing source area simulations, the 8 percent and 15 percent management systems rankings illustrate a predominant management system for a given rank. Examining results for simulations using the 8 percent CSA, Management System 6 was ranked first for 47.2 percent of the simulations compared to 16.7 percent for the next highest management system; Management System 2 ranked second for 41.7 percent of the simulations compared to 16.7 percent for the next highest management system; Management System 1 ranked third for 41.7 percent of the simulations compared to 13.9 percent for the next highest simulation. On the other end of the rankings, Management System 3 ranked last during 41.7 percent of the simulations compared to the next highest last place ranking of 19.4 percent (Management System 4).

Results from the 15 percent CSA were similar to the 8 percent CSA in that for most ranks, there was a discrepancy between the most frequently ranked management system and the other management systems. Ranking 1 had Management System 6 as the lowest sediment yield producing management system during 44.4 percent of the simulations compared to the second most frequent at 22.2 percent of the simulations. At the other end of the rankings, Management System 3 was ranked last during 41.7 percent of the simulations compared to Management System 4 which was ranked last the second most frequent, during 16.7 percent of the simulations.

The IFSAR 2.5 meter digital elevation model produced ranking frequencies with large differences for each rank between the most frequently ranked management system and the second most frequently ranked management system. Management System 6 was ranked first during 55.6 percent of the simulations compared to the next highest management system, Management System 5, which was ranked first during 16.7 percent of the simulations. The closest ranking frequency was for management systems ranked third where Management System 1 was ranked third during 38.9 percent of the simulations compared to Management System 3 which was ranked third during 27.8 percent of the simulations.

The other five digital elevation models had smaller differences in frequencies compared to the IFSAR 2.5 meter data. Management System 6 was ranked first during 61.1 percent of the simulations using the USGS 30 meter DEM while Management System 1 was ranked first during 22.2 percent of the simulations. However, for the same DEM, Management Systems 3 and 4 both ranked fourth during 27.8 percent of the simulations, and Management System 3 and 5 were the most frequent fifth ranked management system, during 27.9 percent of the simulations.

Management system rankings for simulations using the Walnut Gulch 10 meter DEM were relatively inconsistent.

For each rank, differences between the most frequent and second most frequent management system were 22.2, 5.6, 11.1, 22.2, 11.1, and 0 respectively. For example, for the sixth ranked position, the two most frequent management systems, Management System 4 and 5, occurred during the same percentage of simulations, 33.3 percent.

The SRTM 90 meter DEM, which is the most available and has the largest cell size, produced the least consistent rankings of the DEMs used in this analysis. Four of the six rankings, Rankings 1, 2, 3, and 5, had the same percentage for the two most frequent management systems, 33.3 percent. The difference between the two most frequent rankings for the sixth (and last) place ranking was 8.3 percentage points while the difference between the top two fourth ranked management systems was 16.7 percent. It should be pointed out that the number of simulations using the SRTM 90 meter data was the lowest compared to the other DEMs.

Smaller precipitation event sizes produce greater differences between management system rankings than larger precipitation event sizes. Simulations using the two five-year precipitation events (Table 6.11) produced a management system with at least 17.7 percent difference between the most frequent and second most frequent management system, with the exception of the fifth ranked position (2.9 percent difference). The greatest difference between the most frequent and second most frequent management system was for rank 1 which had a difference of 73.5 percent. The 10-year and 100-year precipitation event sizes had smaller differences between management system ranking frequencies (Tables 6.12 and 6.13). For the “best” management system using both the 10-year and 100-year precipitation events, the difference between the most frequent and second most frequent management system was 3.0 percent. The average difference between the most frequent and second most frequent management system for each rank was 3.4 and 6.9 percent for simulations using the 10-year and 100-year precipitation events, respectively.

Table 6.1 Frequency of management system rankings for all simulations with 3 CSA values (1.5, 8, and 15%), 6 DEMs (IFSAR 2.5M, IFSAR 10M, USGS 10M, USGS 30M, WG 10M, and SRTM 90M), and 6 rainfall event sizes (5-yr 30-min, 5-yr 60-min, 10-yr 30-min, 10-yr 60-min, 100-yr 30-min, and 100-yr 60-min) in tabular and graphical format.

	Ranking 1	Ranking 2	Ranking 3	Ranking 4	Ranking 5	Ranking 6	Total Simulations
Management System 1	14.7	16.7	31.4	12.7	15.7	8.8	102
Management System 2	14.7	30.4	16.7	16.7	13.7	7.8	102
Management System 3	2.0	13.7	11.8	12.7	24.5	35.3	102
Management System 4	4.9	12.7	15.7	32.4	12.7	21.6	102
Management System 5	13.7	11.8	9.8	19.6	27.5	17.6	102
Management System 6	50.0	14.7	14.7	5.9	5.9	8.8	102
Total Simulations	102	102	102	102	102	102	

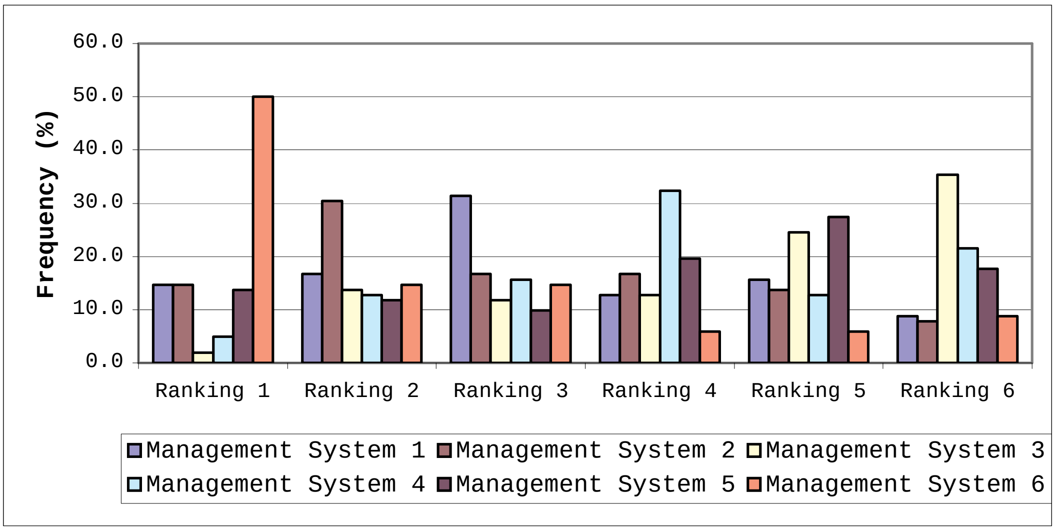


Table 6.2 Frequency of management system rankings for simulations with 1.5% CSA using 6 DEMs (IFSAR 2.5M, IFSAR 10M, USGS 10M, USGS 30M, and WG 10M) and 6 rainfall event sizes (5-yr 30-min, 5-yr 60-min, 10-yr 30-min, 10-yr 60-min, 100-yr 30-min, and 100-yr 60-min) in tabular and graphical format.

	Ranking 1	Ranking 2	Ranking 3	Ranking 4	Ranking 5	Ranking 6	Total Simulations
Management System 1	6.7	26.7	20.0	16.7	20.0	10.0	30
Management System 2	20.0	13.3	20.0	10.0	23.3	13.3	30
Management System 3	0.0	16.7	23.3	16.7	23.3	20.0	30
Management System 4	3.3	6.7	20.0	23.3	16.7	30.0	30
Management System 5	10.0	13.3	10.0	30.0	13.3	23.3	30
Management System 6	60.0	23.3	6.7	3.3	3.3	3.3	30
Total Simulations	30	30	30	30	30	30	

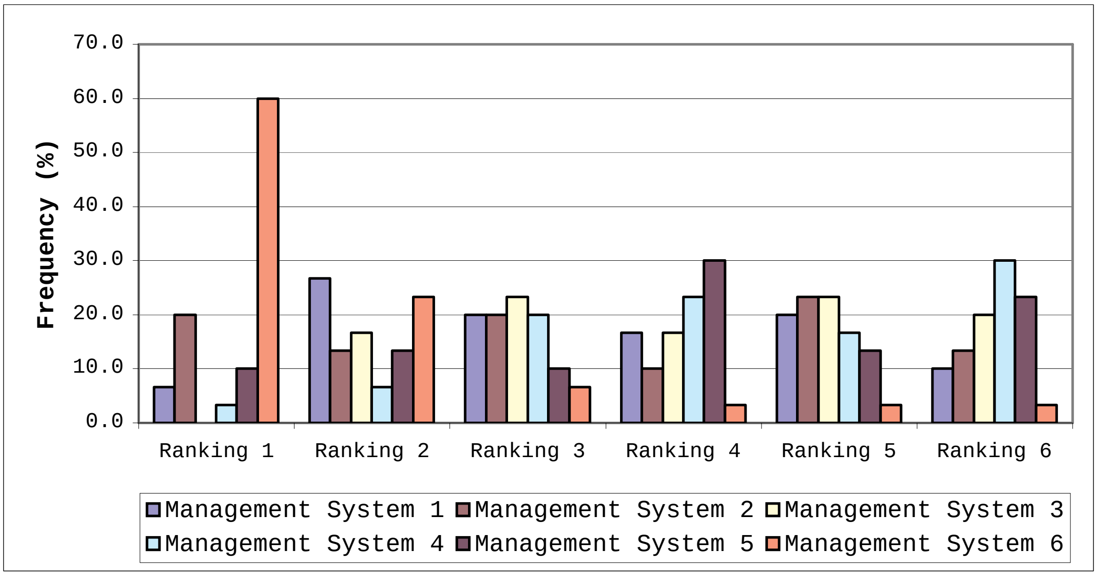


Table 6.3 Frequency of management system rankings for simulations with 8% CSA using 6 DEMs (IFSAR 2.5M, IFSAR 10M, USGS 10M, USGS 30M, WG 10M, and SRTM 90M) and 6 rainfall event sizes (5-yr 30-min, 5-yr 60-min, 10-yr 30-min, 10-yr 60-min, 100-yr 30-min, and 100-yr 60-min) in tabular and graphical format.

	Ranking 1	Ranking 2	Ranking 3	Ranking 4	Ranking 5	Ranking 6	Total Simulations
Management System 1	13.9	11.1	41.7	11.1	13.9	8.3	36
Management System 2	16.7	41.7	13.9	16.7	5.6	5.6	36
Management System 3	2.8	8.3	8.3	13.9	25.0	41.7	36
Management System 4	5.6	16.7	11.1	33.3	13.9	19.4	36
Management System 5	13.9	11.1	13.9	11.1	33.3	16.7	36
Management System 6	47.2	11.1	11.1	13.9	8.3	8.3	36
Total Simulations	36	36	36	36	36	36	

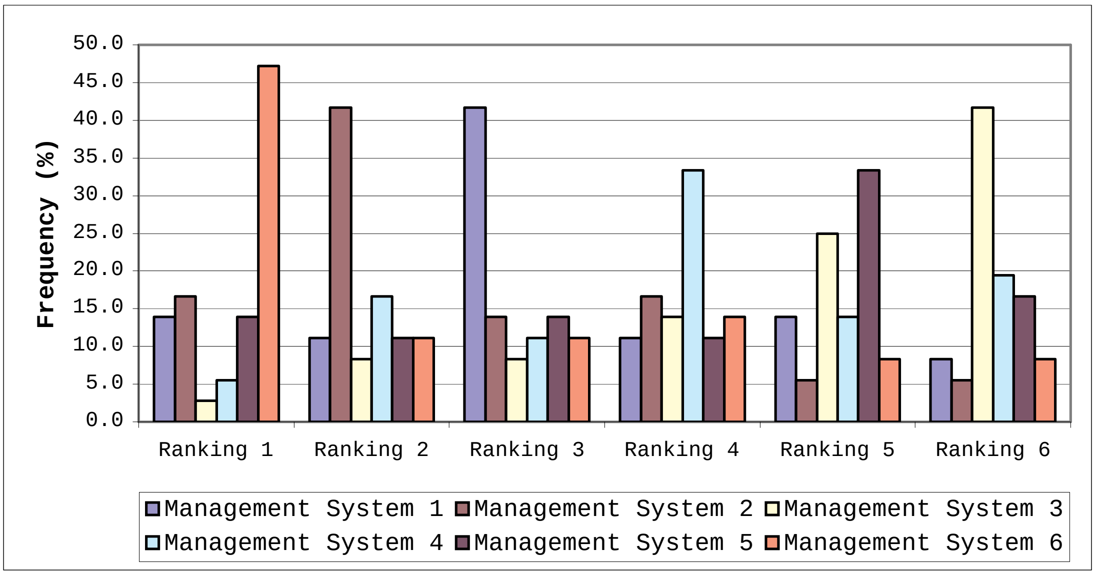


Table 6.4 Frequency of management system rankings for simulations with 15% CSA using 6 DEMs (IFSAR 2.5M, IFSAR 10M, USGS 10M, USGS 30M, WG 10M, and SRTM 90M) and 6 rainfall event sizes (5-yr 30-min, 5-yr 60-min, 10-yr 30-min, 10-yr 60-min, 100-yr 30-min, and 100-yr 60-min) in tabular and graphical format.

	Ranking 1	Ranking 2	Ranking 3	Ranking 4	Ranking 5	Ranking 6	Total Simulations
Management System 1	22.2	13.9	30.6	11.1	13.9	8.3	36
Management System 2	8.3	33.3	16.7	22.2	13.9	5.6	36
Management System 3	2.8	16.7	5.6	8.3	25.0	41.7	36
Management System 4	5.6	13.9	16.7	38.9	8.3	16.7	36
Management System 5	16.7	11.1	5.6	19.4	33.3	13.9	36
Management System 6	44.4	11.1	25.0	0.0	5.6	13.9	36
Total Simulations	36	36	36	36	36	36	

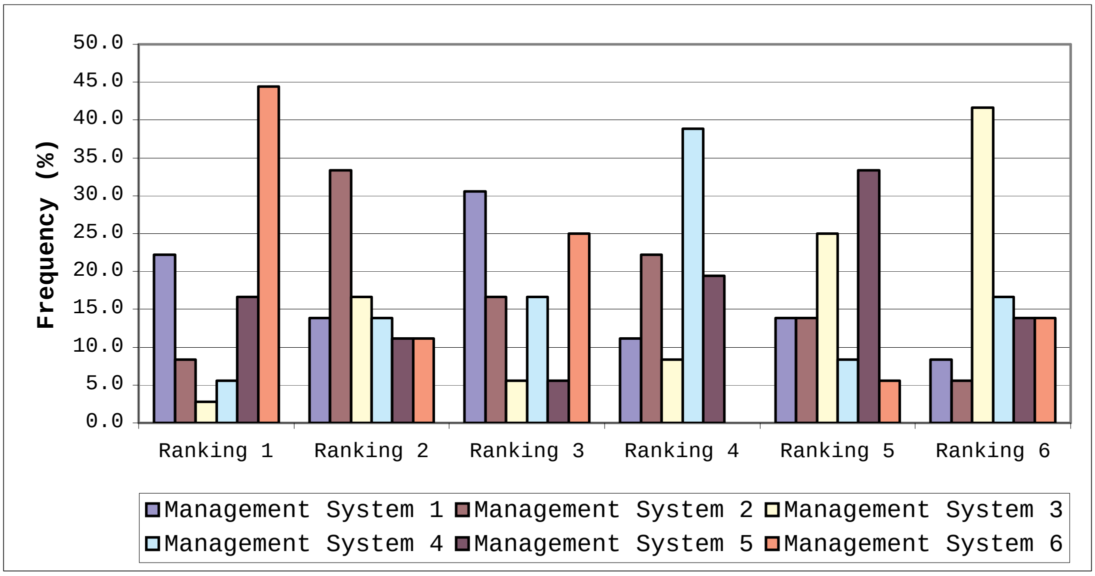


Table 6.5 Frequency of management system rankings for simulations with IFSAR 2.5M DEM using 3 CSA values (1.5, 8, and 15%) and 6 rainfall event sizes (5-yr 30-min, 5-yr 60-min, 10-yr 30-min, 10-yr 60-min, 100-yr 30-min, and 100-yr 60-min) in tabular and graphical format.

	Ranking 1	Ranking 2	Ranking 3	Ranking 4	Ranking 5	Ranking 6	Total Simulations
Management System 1	5.6	11.1	38.9	11.1	16.7	16.7	18
Management System 2	11.1	50.0	11.1	5.6	16.7	5.6	18
Management System 3	0.0	5.6	27.8	5.6	11.1	50.0	18
Management System 4	11.1	16.7	11.1	44.4	11.1	5.6	18
Management System 5	16.7	11.1	0.0	16.7	38.9	16.7	18
Management System 6	55.6	5.6	11.1	16.7	5.6	5.6	18
Total Simulations	18	18	18	18	18	18	

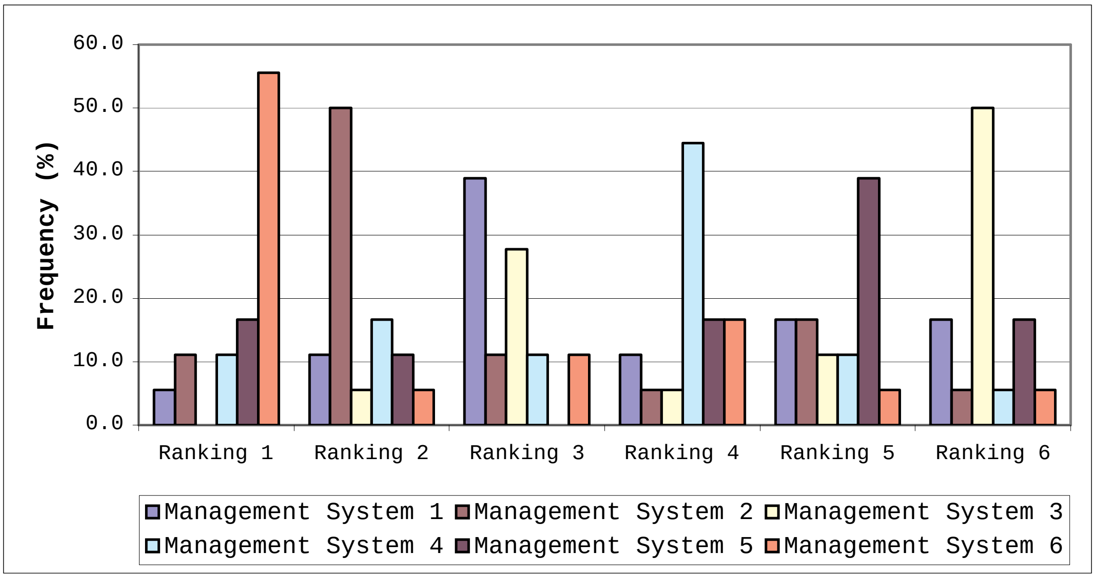


Table 6.6 Frequency of management system rankings for simulations with IFSAR 10M DEM using 3 CSA values (1.5, 8, and 15%) and 6 rainfall event sizes (5-yr 30-min, 5-yr 60-min, 10-yr 30-min, 10-yr 60-min, 100-yr 30-min, and 100-yr 60-min) in tabular and graphical format.

	Ranking 1	Ranking 2	Ranking 3	Ranking 4	Ranking 5	Ranking 6	Total Simulations
Management System 1	22.2	5.6	44.4	11.1	11.1	5.6	18
Management System 2	16.7	16.7	22.2	5.6	16.7	22.2	18
Management System 3	0.0	27.8	11.1	5.6	11.1	44.4	18
Management System 4	0.0	11.1	5.6	33.3	27.8	22.2	18
Management System 5	22.2	5.6	5.6	44.4	22.2	0.0	18
Management System 6	38.9	33.3	11.1	0.0	11.1	5.6	18
Total Simulations	18	18	18	18	18	18	

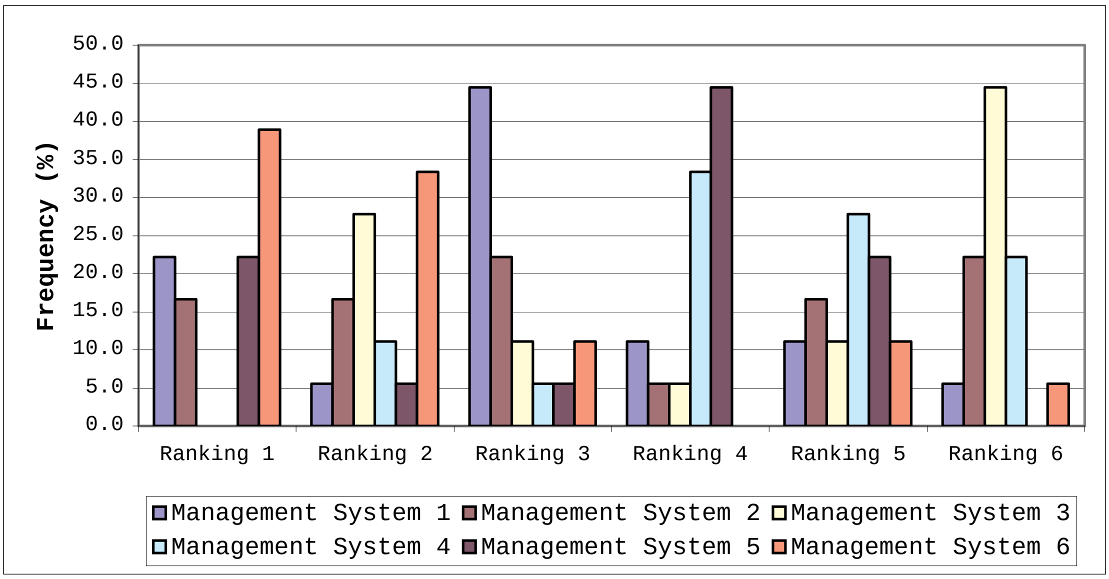


Table 6.7 Frequency of management system rankings for simulations with USGS 10M DEM using 3 CSA values (1.5, 8, and 15%) and 6 rainfall event sizes (5-yr 30-min, 5-yr 60-min, 10-yr 30-min, 10-yr 60-min, 100-yr 30-min, and 100-yr 60-min) in tabular and graphical format.

	Ranking 1	Ranking 2	Ranking 3	Ranking 4	Ranking 5	Ranking 6	Total Simulations
Management System 1	11.1	22.2	22.2	33.3	5.6	5.6	18
Management System 2	16.7	33.3	22.2	11.1	11.1	5.6	18
Management System 3	0.0	5.6	16.7	11.1	27.8	38.9	18
Management System 4	5.6	16.7	16.7	27.8	5.6	27.8	18
Management System 5	0.0	16.7	11.1	16.7	38.9	16.7	18
Management System 6	66.7	5.6	11.1	0.0	11.1	5.6	18
Total Simulations	18	18	18	18	18	18	

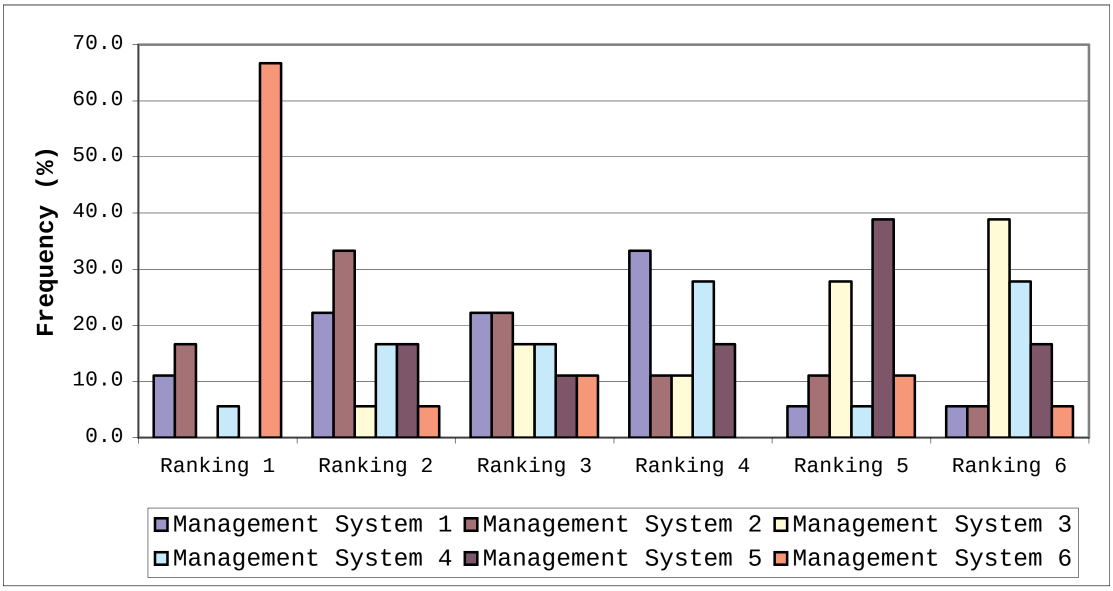


Table 6.8 Frequency of management system rankings for simulations with USGS 30M DEM using 3 CSA values (1.5, 8, and 15%) and 6 rainfall event sizes (5-yr 30-min, 5-yr 60-min, 10-yr 30-min, 10-yr 60-min, 100-yr 30-min, and 100-yr 60-min) in tabular and graphical format.

	Ranking 1	Ranking 2	Ranking 3	Ranking 4	Ranking 5	Ranking 6	Total Simulations
Management System 1	22.2	27.8	22.2	11.1	5.6	11.1	18
Management System 2	16.7	22.2	16.7	11.1	22.2	11.1	18
Management System 3	0.0	0.0	0.0	27.8	27.8	44.4	18
Management System 4	0.0	16.7	33.3	27.8	11.1	11.1	18
Management System 5	0.0	22.2	16.7	16.7	27.8	16.7	18
Management System 6	61.1	11.1	11.1	5.6	5.6	5.6	18
Total Simulations	18	18	18	18	18	18	

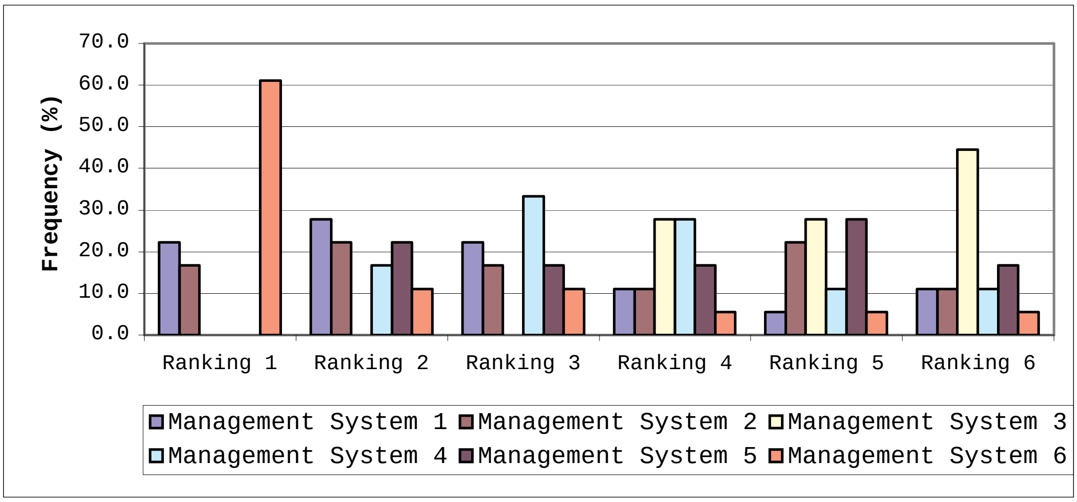


Table 6.9 Frequency of management system rankings for simulations with Walnut Gulch 10M DEM using 3 CSA values (1.5, 8, and 15%) and 6 rainfall event sizes (5-yr 30-min, 5-yr 60-min, 10-yr 30-min, 10-yr 60-min, 100-yr 30-min, and 100-yr 60-min) in tabular and graphical format.

	Ranking 1	Ranking 2	Ranking 3	Ranking 4	Ranking 5	Ranking 6	Total Simulations
Management System 1	11.1	16.7	27.8	5.6	27.8	11.1	18
Management System 2	11.1	27.8	16.7	38.9	5.6	0.0	18
Management System 3	11.1	16.7	5.6	16.7	38.9	11.1	18
Management System 4	11.1	11.1	16.7	16.7	11.1	33.3	18
Management System 5	16.7	5.6	16.7	11.1	16.7	33.3	18
Management System 6	38.9	22.2	16.7	11.1	0.0	11.1	18
Total Simulations	18	18	18	18	18	18	

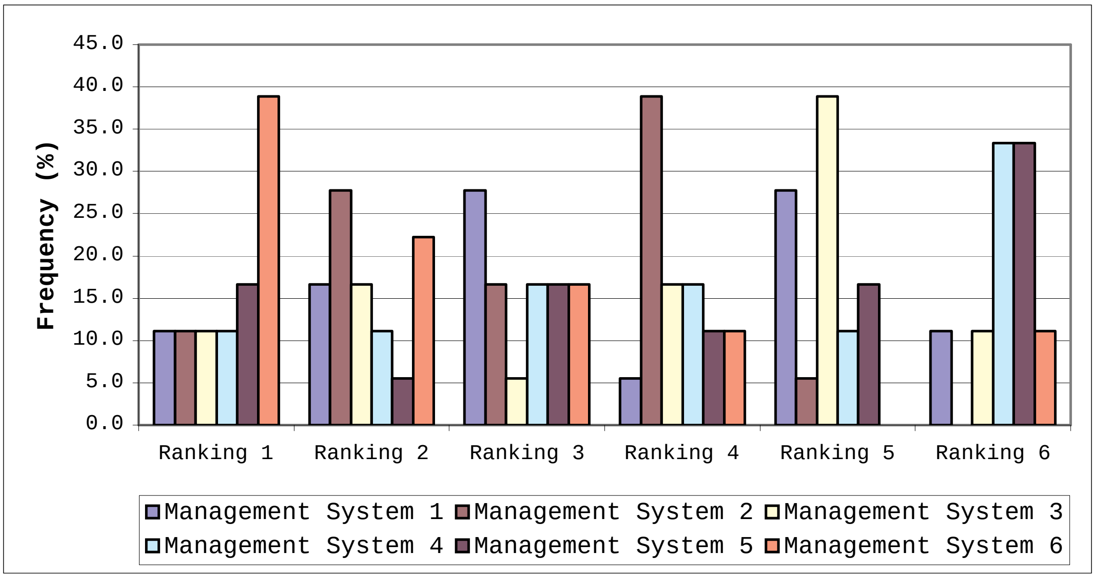


Table 6.10 Frequency of management system rankings for simulations with Shuttle Radar Topography Mission 90M DEM using 3 CSA values (1.5, 8, and 15%) and 6 rainfall event sizes (5-yr 30-min, 5-yr 60-min, 10-yr 30-min, 10-yr 60-min, 100-yr 30-min, and 100-yr 60-min) in tabular and graphical format.

	Ranking 1	Ranking 2	Ranking 3	Ranking 4	Ranking 5	Ranking 6	Total Simulations
Management System 1	16.7	16.7	33.3	0.0	33.3	0.0	12
Management System 2	16.7	33.3	8.3	33.3	8.3	0.0	12
Management System 3	0.0	33.3	8.3	8.3	33.3	16.7	12
Management System 4	0.0	0.0	8.3	50.0	8.3	33.3	12
Management System 5	33.3	8.3	8.3	8.3	16.7	25.0	12
Management System 6	33.3	8.3	33.3	0.0	0.0	25.0	12
Total Simulations	12	12	12	12	12	12	

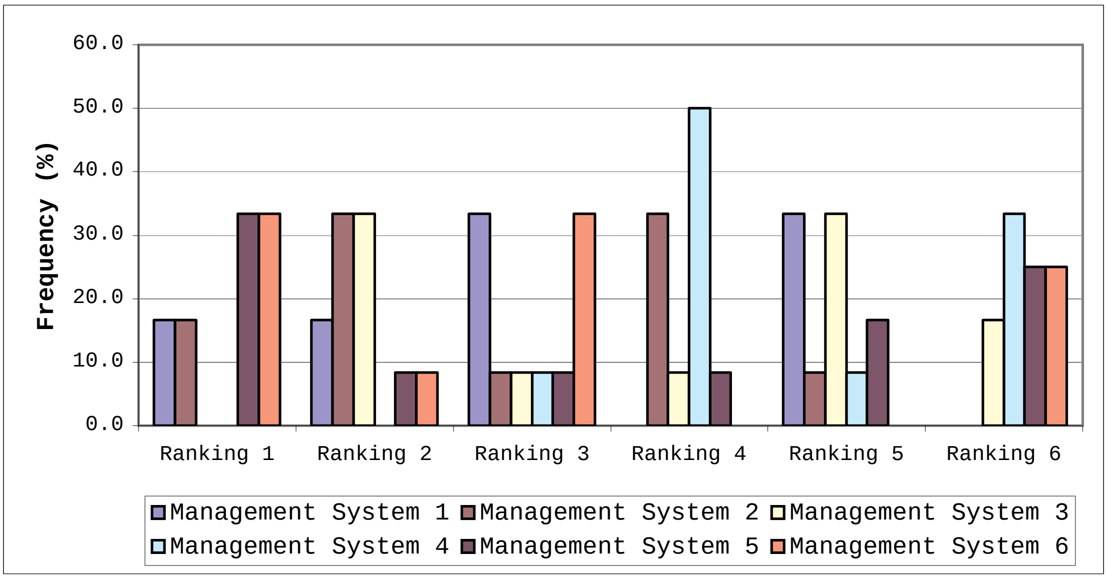


Table 6.11 Frequency of management system rankings for simulations with 5 year return period rainfall events using 3 CSA values (1.5, 8, and 15%), 6 DEMs (IFSAR 2.5M, IFSAR 10M, USGS 10M, USGS 30M, WG 10M, and SRTM 90M) and 2 rainfall durations (30-min and 60-min) in tabular and graphical format.

	Ranking 1	Ranking 2	Ranking 3	Ranking 4	Ranking 5	Ranking 6	Total Simulations
Management System 1	11.8	20.6	44.1	14.7	5.9	2.9	34
Management System 2	0.0	52.9	23.5	17.6	2.9	2.9	34
Management System 3	2.9	0.0	5.9	5.9	38.2	47.1	34
Management System 4	0.0	2.9	17.6	44.1	17.6	17.6	34
Management System 5	0.0	8.8	8.8	17.6	35.3	29.4	34
Management System 6	85.3	14.7	0.0	0.0	0.0	0.0	34
Total Simulations	34	34	34	34	34	34	

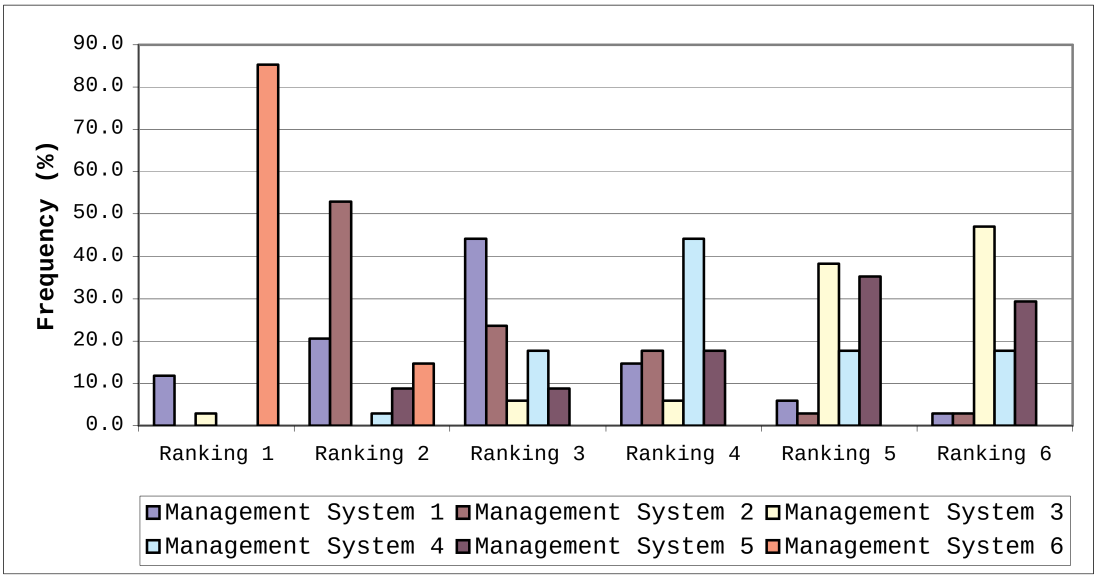


Table 6.12 Frequency of management system rankings for simulations with 10 year return period rainfall events using 3 CSA values (1.5, 8, and 15%), 6 DEMs (IFSAR 2.5M, IFSAR 10M, USGS 10M, USGS 30M, WG 10M, and SRTM 90M) and 2 rainfall durations (30-min and 60-min) in tabular and graphical format.

	Ranking 1	Ranking 2	Ranking 3	Ranking 4	Ranking 5	Ranking 6	Total Simulations
Management System 1	14.7	17.6	17.6	11.8	23.5	14.7	34
Management System 2	29.4	17.6	17.6	8.8	14.7	11.8	34
Management System 3	0.0	8.8	14.7	26.5	23.5	26.5	34
Management System 4	11.8	26.5	14.7	14.7	14.7	17.6	34
Management System 5	11.8	8.8	17.6	32.4	20.6	8.8	34
Management System 6	32.4	20.6	17.6	5.9	2.9	20.6	34
Total Simulations	34	34	34	34	34	34	

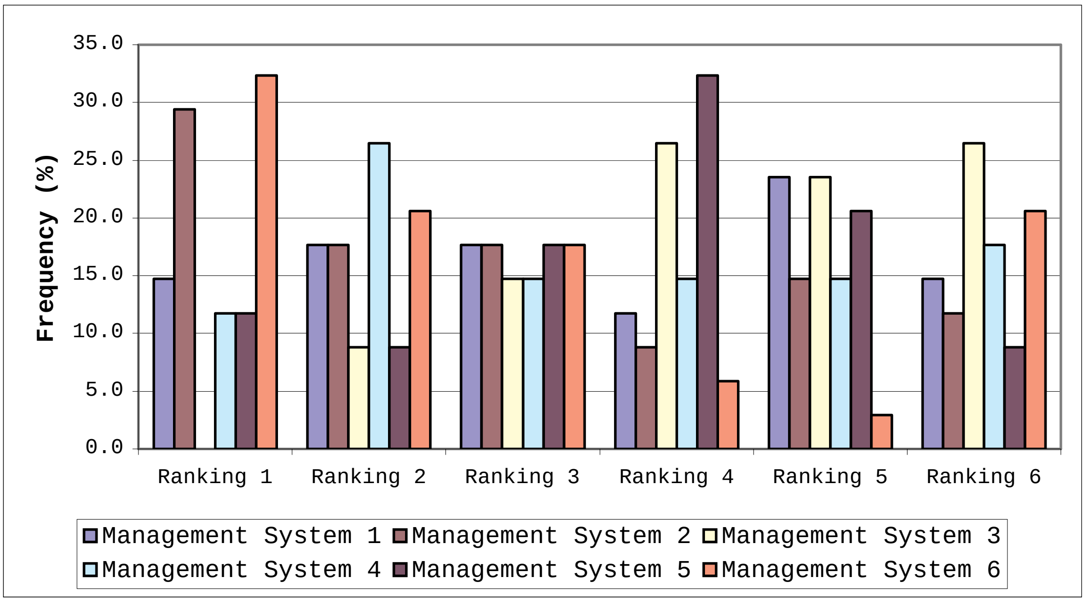
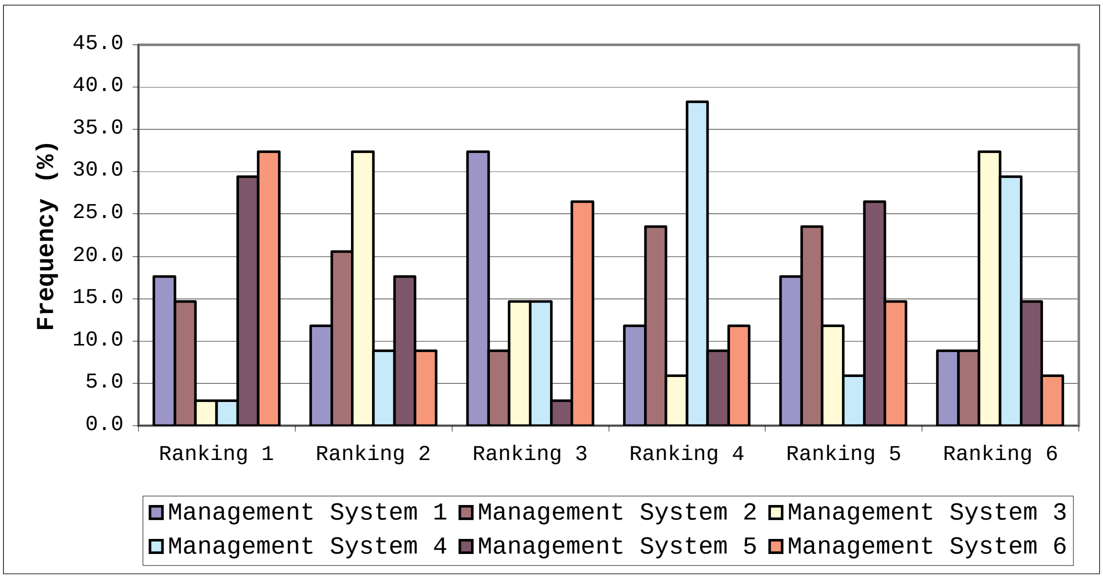


Table 6.13 Frequency of management system rankings for simulations with 100 year return period rainfall events using 3 CSA values (1.5, 8, and 15%), 6 DEMs (IFSAR 2.5M, IFSAR 10M, USGS 10M, USGS 30M, WG 10M, and SRTM 90M) and 2 rainfall durations (30-min and 60-min) in tabular and graphical format.

	Ranking 1	Ranking 2	Ranking 3	Ranking 4	Ranking 5	Ranking 6	Total Simulations
Management System 1	17.6	11.8	32.4	11.8	17.6	8.8	34
Management System 2	14.7	20.6	8.8	23.5	23.5	8.8	34
Management System 3	2.9	32.4	14.7	5.9	11.8	32.4	34
Management System 4	2.9	8.8	14.7	38.2	5.9	29.4	34
Management System 5	29.4	17.6	2.9	8.8	26.5	14.7	34
Management System 6	32.4	8.8	26.5	11.8	14.7	5.9	34
Total Simulations	34	34	34	34	34	34	



6.4. Discussion

The “best” and “worst” management system would ideally be determined by conducting a well designed study that monitors the hydrologic impact over long time periods (i.e. 10 to 50 years). However, this approach has a number of problems. First, management decisions are site-specific based on local information such as soils, topography, and vegetation. Therefore, this type of management system evaluation would have to be conducted at each location to determine which management system is “best”. Monitoring studies are expensive and in many cases funds are not available. In addition, different management systems would need to be implemented, monitored, and replaced with a alternative management system to determine which management system is the “best” system for a given location.

Because using monitoring data to evaluate different management systems is impractical from a cost and time standpoint, management decisions modeling efforts are one option to determine the “best” system to implement. However, using hydrologic models has problems related to uncertainty in input data and physical process representation. Input geographic data are available at different resolutions and qualities leading to challenges in selecting the most appropriate data for a given task. The highest resolution data are often perceived as the “best” which might not be the best data to use for watershed scale modeling. As illustrated by results in this chapter, the highest resolution and most accurate DEM was the 2.5 meter IFSAR data. Simulation results using the “most accurate” DEM had the highest sediment yield values because of the high slope values. On the contrary, simulations for Watershed 11 using the lowest resolution and least accurate DEM (SRTM 90 DEM) did not produce sediment yield results that would allow a manager to differentiate between the different management systems.

Just as important as selecting the digital elevation model to use in the modeling effort is the selection of the contributing source area and the precipitation event size. Varying these values had a greater influence in differentiating between the management systems than of the DEMs. Although the smallest CSA value (1.5 percent) produced inconsistent management system rankings, the two larger CSA values (8.0 and 15.0 percent) provided separation of sediment yield values between the six management systems. The reason for this effect of CSA values results from the interaction between the geometric representation of the watershed and the hydrologic processes representation in the model.

Configurations with smaller contributing source area values have greater total channel lengths. Conversely, configurations with larger contributing source area values have smaller total channel length. As a result, simulations are less sensitive to changes on upland characteristics for smaller CSA configurations because the channel processes mask effects resulting from changes in upland characteristics. As the CSA value increases, the upland effects of the management system becomes more important and have a greater influence on sediment yield estimates.

The influence of precipitation event size on estimated sediment yield results from site characteristics being more influential for smaller event sizes than larger event sizes. For smaller precipitation events, site characteristics such as vegetative cover and soil properties have a greater influence on runoff generating mechanisms. Conversely, vegetation and soil characteristics have little influence on runoff for larger precipitation events. Therefore, different management systems exhibit greater influences on sediment yield for smaller precipitation events compared to larger precipitation events.

6.5. Summary and Conclusions

Rankings from the spatial decision support system were compared using combinations of different configuration and source data for six management systems. Simulations were performed for Watershed 11 in the Walnut Gulch Experimental Watershed using watershed configurations from six different digital elevation models of different resolutions and accuracy, three different contributing source area values, six different precipitation event sizes. Management systems were ranked based on the estimated sediment yield where management systems yielding the lower sediment yield values were considered better.

The selection of digital elevation model, contributing source area, and precipitation event size will impact the rankings by the spatial decision support system. Of the three CSA values (1.5, 8.0, and 15 percent), the 1.5 percent CSA produced the least consistent management system rankings while the 8 percent CSA value produced the most consistent rankings. The smaller, more frequent rainfall event (5-year return period) had more consistent management system rankings while the larger, less frequent rainfall event (100-year return period) produced less consistent management system rakings. Of the six digital elevation models, the highest resolution DEM (2.5 meter IFSAR) had the most consistent management system rankings while the lowest resolution DEM (90 meter SRTM) had the least consistent management system rankings.

Examining ranking frequencies across the DEMs illustrated a few relationships of note. The IFSAR 2.5 meter and USGS 10 meter DEMs had management system ranking frequencies that were the most similar even though these DEMs were created using different methods. This indicates that the selection of DEM for use in the spatial decision support system should not be based on derivation method as

DEMs derived using the same methods had different rankings. For example, ranking frequencies for simulations using the IFSAR 10 meter DEM, which is derived from the IFSAR 2.5 meter DEM, were the same as the IFSAR 2.5 meter DEM in only three of the six positions (first, third, and last). However, all of the DEMs had Management System 6 ranked as producing the lowest sediment yield the most frequently.

Simulations using the 8 percent CSA with the 10-year 60-minute storm event minimized the influence of the DEM on management system rankings; for this configuration, the DEM selection had the smallest impact on changing management rankings. For these simulations, four of the six DEMs produced the same rankings while the remaining two DEMs produced identical rankings. Digital elevation model selection had the greatest influence on simulations using the 0.5 percent CSA value, as none of the order of management system rankings for a DEM were the same.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1. Introduction

Information technology has drastically changed watershed management in the past few decades. Advances in technologies such as the Internet, geographic information systems, remote sensing, and spatial databases have improved the manner in which we communicate and exchange information, collect, process and visualize spatial data, and represent and store information. Information technology allows watershed managers to be much more efficient, for example procedures such as hydrologic model parameterizations can be conducted in minutes, which could take weeks when conducted manually.

While information technology has profoundly impacted watershed management, opportunities continue as technology and environmental decision-making changes. As management decisions tend towards a bottom-up approach, which involves stakeholders through the decision process, information technology can assist communication and education of those involved. The Internet provides an efficient medium for transfer and sharing of information among decision makers. The availability and access to data allows local stakeholders to use current information and perform analyses and educate themselves regarding complexities of the issues. Moreover, empowering local stakeholders results in bi-directional communication and increases chances for consensus among stakeholders.

The success of bottom-up decision-making relies on educating stakeholders about the problems and the processes causing the problems. Providing access to decision support systems offers the opportunity to integrate the social-economic and biophysical processes into a framework accessible to local stakeholders. Decision support systems integrate simulation models describing the physical processes, geographic information systems capturing the spatial nature of the information, and the Internet providing access to information to those involved and when combined with other technologies, offer potential to convert data to information to knowledge. This data-information-knowledge conversion provides the opportunity to offer decision-makers with data in appropriate formats, a need identified by the National Research Council (1999).

7.2. Major Contributions

The research conducted led to the design and implementation of a prototype Internet-based spatial decision support system (SDSS) for rangeland watershed management. The Internet-based SDSS provides core functionality required for rangeland watershed management education and decision-making. Users have the capability to dynamically delineate watersheds by clicking on a map to locate a watershed outlet. Using this boundary, users can perform simulations using hydrologic models with parameter sets derived from soils and land cover GIS data layers and spatially visualize results. The application provides a “thicker” client to delineate rangeland management systems which consist of pasture boundaries, water points, and sediment detention structures. Each management practice contains user-defined attributes that are incorporated into the modeling process. Hydrologic simulations are performed on user delineated management systems and results are presented in a spatial, graphical, and tabular format. Users can create “what if” scenarios such as locating water sources at different locations within a pasture or change the location of pasture boundaries and compare the runoff and sediment yield of different scenarios.

The important contributions of this research to the literature on decision support systems are:

§ Analysis and documentation of the requirements for a spatial decision support system for rangeland watershed management.

§ Implementation of the spatial decision support system providing a fully interactive GIS over the Internet.

§ Evaluation of error in readily available digital elevation models.

§ Determination of the sensitivity of digital elevation models, contributing source area values, and precipitation event sizes on management systems rankings by the spatial decision support system.

7.3. Major Conclusions

Results from this study yielded several conclusions relevant to the field of watershed hydrology and management. The major conclusions include:

- Recent advances in information technology can be effectively utilized in watershed decision support technology. Spatial decision support systems can leverage IT advances such as Web services, object oriented design methods, and the Internet to produce the next generation of watershed applications. Applications using Web services promote component reuse and sharing across operating systems and programming languages. Furthermore, when Web services are combined with the Internet, this technology promotes sharing of research and development across organizations. Deploying watershed applications via the Internet increases access to underrepresented stakeholders. The Internet provides a means to link diverse stakeholders while simplifying application management and updates. And finally, object oriented principles are well suited for the complexities related to different hydrologic models and ontologic representations for watersheds. Inheritance and polymorphism allow multiple models to be included in the spatial decision support system with little effort.

§ In comparing digital elevation data of different sources and resolutions with survey data, the digital data approximated surfaces well, with the higher resolution data producing lower root mean square error values. The DEMs represented the hilly region of the Walnut Gulch Experimental Watershed better than the highly dissected region of the watershed. For the highly dissected area, the lower resolution DEMs had difficulty capturing tops of ridges and bottoms of head-cuts. Because highly dissected regions are important sediment producing areas, using the lower resolution DEMs included in this analysis would ignore erosion processes in these areas which may impact total sediment predicted from hydrologic simulations. The USGS 10 meter DEM, which is highest resolution, most widely available digital elevation model, did not capture these sediment producing areas on Walnut Gulch. As expected, the 90-meter Shuttle Radar Topography Mission data did not capture small watershed features. The small watersheds delineated with the 30-meter resolution digital data compared reasonably well with digitized watershed boundaries. However, the higher resolution digital data (2.5 and 10 meter data) created watershed boundaries that most closely matched digitized data.

§ Different digital elevation models, contributing source area values, and precipitation event sizes produced different management system rankings. Differences in the frequencies of management system rankings were greater for the smaller precipitation event sizes and middle and larger contributing source area values compared to the different DEMs. This greater difference in frequencies of management system rankings indicates a management system was consistently ranked in a certain position (i.e. fourth) during a greater portion of the simulations.

The selection of digital elevation models produced less conclusive or lower differences between management system rankings compared to contributing source area values and precipitation event sizes. Smaller contributing source area values also produced inclusive frequencies of management system rankings. The DEM that had the lowest resolution of the six DEMs in the study produced inconclusive results for management system rankings. Unfortunately, this DEM, the SRTM 90 meter DEM, is available for North America which decreases the confidence in results from using these data in spatial decision support system simulations.

7.4. Recommendations for Future Research

Providing access to applications such as the spatial decision support system opens doors to future research to evaluate of the role of technology in bottom-up decision-making for watershed management. Once applications are made available to the public, this type of application can be monitored to determine and evaluate users’ preferences about how these types of systems can be implemented. The

SDSS is designed to be simulation model independent, allowing new simulation models to be included, however different models have different assumptions and were developed for different purposes. Research on developing heuristics for constraining the application of these models in both a spatial/temporal context and for specific environmental problems should also be conducted.

In advancing technology for transferring information from scientists to decision-makers, watershed managers and scientists need to be more proactive in defining what is needed specifically from information technology to assist the watershed decision-making process. Advancing Internet GIS through making the transfer of data more efficient allows spatial information to be integrated in applications supplied to decision-makers. Simulation modeling can be improved through two methods: improving the understanding of the processes and improving the representation of the properties. The latter can be addressed through spatial database research developing “smart” data types which embed the characteristics of the data in its representation. Other methods for exploring spatial relationships such as spatial data mining provide opportunities to examine data using techniques yet to be explored in watershed management. For example, preliminary research has been done to distribute soil texture based on a soils position on a hillslope, but these types of relationships have not been studied extensively in different hydrologic regions. And finally, integrating individual applications into decision support systems provides additional information for decision makers.

7.4.1. Internet GIS

As the technology for transferring spatial data via the Internet advances, Internet-based applications will be richer and functionality will increase. Currently, most Internet GIS applications use images to transfer spatial data; a spatial server converts the area selected by the user from raster and/or vector to an image such as a jpeg and the data are transferred. Transferring data in its original format is inefficient and other formats have been examined. Scientists are researching this issue and certain architectures have been proposed for more efficient spatial data transfer. For example, Wei et al. (1999) developed a client-side application using a tile-division method which requires new requests to only transfer data on tiles not present on the client. Since the only two ways to improve performance in Web-based GIS are to increase the speed of the Internet or increase the efficiency of the programs (Peng, 1997), research should focus on increasing the efficiency of the programs.

7.4.2. Spatial Databases

Research on Spatial Database Management Systems is primarily focused on developing a spatial taxonomy, spatial data models, spatial query languages and processing strategies, spatial access methods (Shekhar et al., 1999), and spatial data mining and has been out of the realm of watershed management. However, watershed scientists should actively participate in research for spatial data models and spatial data mining.

7.4.3. Spatial Data Models

Spatial data models are data structures that represent and store features and behaviors of interest. Currently, there are two common types of geographic space models:

entity-based (or object based) and field-based (or cell based). The entity-based model describes geographic space as discrete spatially referenced objects, typically a point, line, or polygon. The field-based models represent geographic space as a tessellation of regular or irregular shaped cells. In most common GISs, field-based data models are regular, rectangular shaped cells for computational simplicity.

Data models specifically developed for hydrology and watershed management can improve the representation in the next generation of simulation models. A data model developed by Dr. David Maidment at the University of Texas, Austin describes an entity-based structure for water resources (see Maidment, 2002). This approach allows natural features found on the landscape to be described in the database and addresses the primary features representing the landscape, how water moves between features, and what are the time patterns associated with each feature (Maidment, 2002). Utilizing a watershed-specific data model will ease the connection between simulation models and data storage resulting in a tighter integration.

Advances in field-based data models could make quad-tree data structures operable in watershed management. Quad-tree data structures provide the benefits of representing landscape features at variable scales over an area. For example, when modeling the effects of riparian vegetation over a watershed using current regular shaped cells, most of the values will be zero or null resulting in large amounts of wasted space. However, with quad-tree data structures, the cell size can change so that smaller cells adjacent to the stream can capture the variability needed to represent riparian properties.

7.4.4. Knowledge Discovery/Spatial Data Mining

The quantity of spatial data is increasing rapidly as new satellites are launched and agencies continue to create data; however, converting this data into information is a very challenging task. Knowledge Discovery is the process of converting data to knowledge and is often perceived along a data-information-knowledge continuum. One step in the Knowledge Discovery process is data mining, which is the process of developing algorithms to extract new patterns from data contained in databases (Buttenfield et al., 2000). Data mining models often utilize statistics, neural networks, and symbolic learning computational approaches, along with evolutionary algorithms, fuzzy sets and fuzzy logic (Chen, 2001). Spatial data mining is the process of examining spatial databases looking for implicit useful information (Chawla et al., 2000). In addition to traditional data mining, spatial data mining provides additional challenges due to difficulties in spatial representation and the spatial autocorrelation inherent in spatial phenomena. In watershed management, applications of spatial data mining have been limited, yet the possibilities for integrating the spatial data mining process in watershed analyses exist.

7.4.5. Evaluation and Verification of Spatial Decision Support Systems

While it is recognized that errors exist in data, their effects on decisions are less clearly understood. For example, the sensitivity of management decisions from spatial decision support systems will vary depending on the resolution and errors inherent in the underlying data sets. However, the impact of the output management system needs to be studied in greater detail. Research in this area will provide information on the quality of data required for decision support systems and the need (or lack of need) for improved information.

Once Spatial Decision Support Systems are assembled, verifying simulation results is complex due to the lack of data and the time-scale required for natural systems to respond to management alterations. Since one reason for the low adoption rates of decision support system is lack of field validation (Newman et al., 2000), the development of decision support systems must include attempts to verify simulation results; however verifying these systems is a complex and difficult task. One approach is to verify the individual components of the system independently, but this approach neglects the interaction and feedback among processes. Verifying the entire system requires long-term data records and an understanding of the interactions between involved processes.

7.4.6. Defining XML Standards

Extensible Markup Language (XML) provides the capability of integrating different incompatible technologies through the use of a structured, open file format. Defining an XML standard schema allows different applications to share information. For example, a decision support system communicating with watershed-scale hydrologic simulation models through XML allows the system to utilize different simulation models. And since different simulation models are applicable to different environments, the appropriate models could be used. A standard schema also allows applications to be distributed, communicating through the network.

7.4.7. Specialization through Web Services

Internet technology has provided a means for communication between agencies with different expertise regarding natural resources management. However, due to various constraints, communication and utilization of this expertise is limited. One of the areas yet to be explored in watershed management is the use of Web services to integrate agency expertise in the decision-making process. Web services are a new breed of web applications that can be accessed from other applications or by other Web services and provide their own implementation of application logic hosted at various locations. For watershed management, the different components of a spatial decision support system could be implemented using Web services. The hypothetical architecture involves federal, state, and local stakeholders all contributing their expertise to the decision process. An agency such as the US Forest Service might have a Web service that determines the locations of logging roads or forest management plans based on available data. The US Fish and Wildlife service might have a Web service that provides information about Threatened and Endangered species for the same area. This technology, while still in its infancy, has the capability to integrate stakeholder concerns and potentially streamline the decision-making process.

APPENDIXES

Appendix A: Definition of Terminology

Abstract class – A class that cannot be instantiated. An abstract class is used where the implementation of methods is common to all subclasses but other methods must contain the implementation.

Applet – an applet is a program written using the Java programming language that can be included in an HTML page, much in the same way an image is included. (From http://java.sun.com/applets/).

Concrete class – An instantiable class that contains the implementation details.

Enterprise JavaBean – A server-side component architecture available through the Java 2 Enterprise Edition environment.

Extensible – capable of being extended with new or additional functionality.

eXtensible Markup Language (XML) – A text based document structure that identifies the content of text by using a tag-based hierarchy.

Inheritance – Ability of a sub-class to utilize functionality of a super class, i.e. a subclass inherits the super class

Class Interface – A definition of the functionality provided by a class. A class interface does not contain details on how the functionality is implemented, only details on what the class can do.

Interoperable - interoperability is the ability of systems or software components of a system to operate reciprocally overcoming barriers imposed by heterogeneous processing environments and heterogeneous data (Buehler and Mckee, 1998)

Object-oriented Programming – a structure of programming based on objects that represent real world items.

Polymorphism – The invocation of the appropriate object method depending on where the object is in the inheritance hierarchy (Horstmann and Cornell, 1999)

Web Services – Components that communicate using text (XML) based messages. This Web services architecture eliminates programming language, operating system, database management system, and hardware dependencies.

Appendix B: SDSS Screen Captures

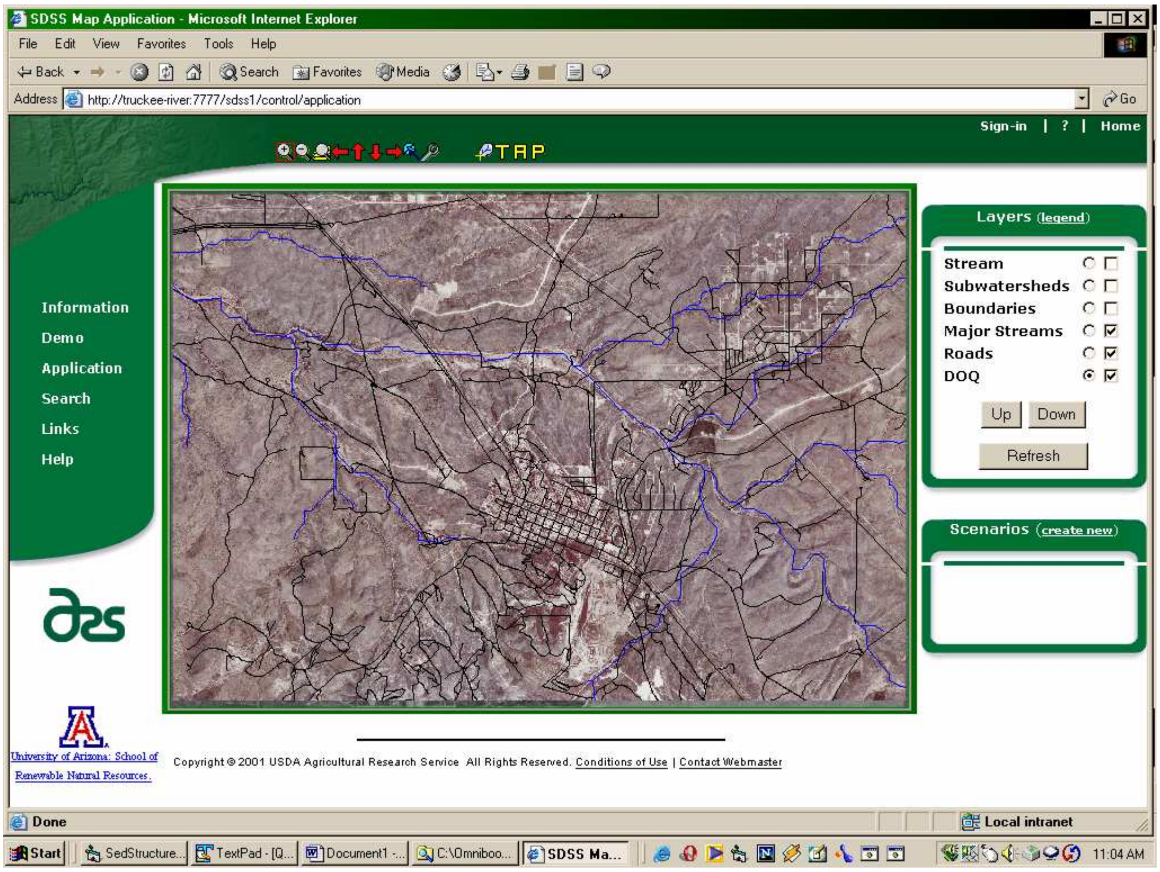


Figure B.1. The SDSS provides users with basic GIS functionality. Users can move layers up/down, turn layers off/on, and zoom in/out.

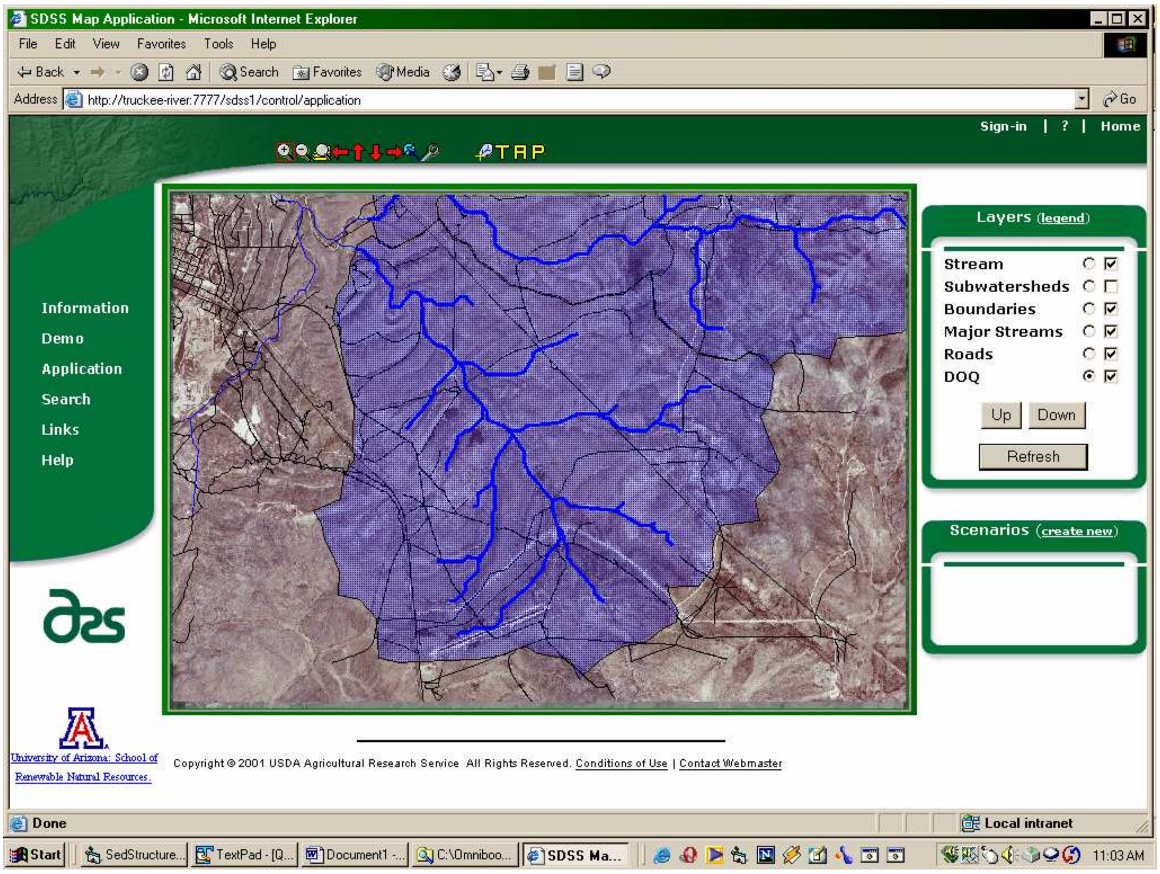


Figure B.2. Users can delineate watershed boundaries by locating the watershed outlet by "clicking" on a map

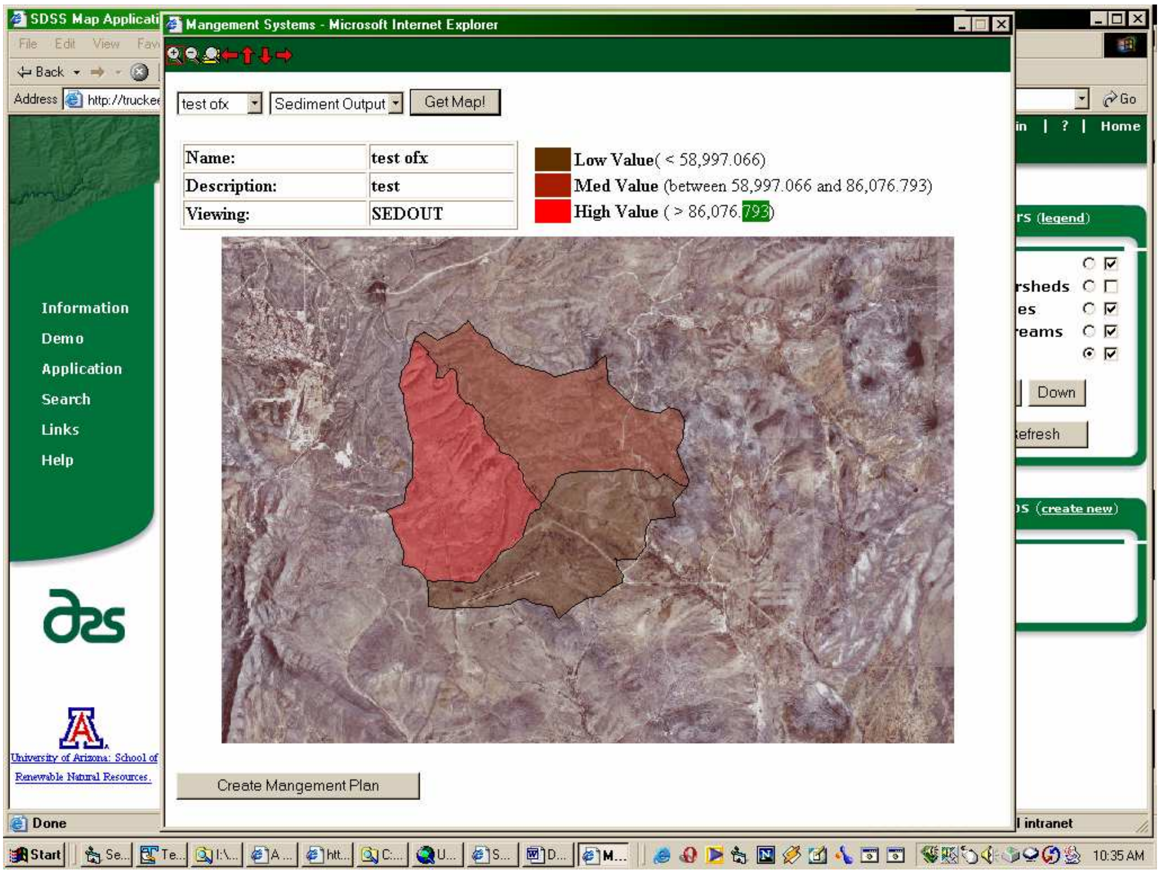


Figure B.3. Results from the simulations can be displayed spatially on the map. Users have the option to view runoff or sediment yield data.

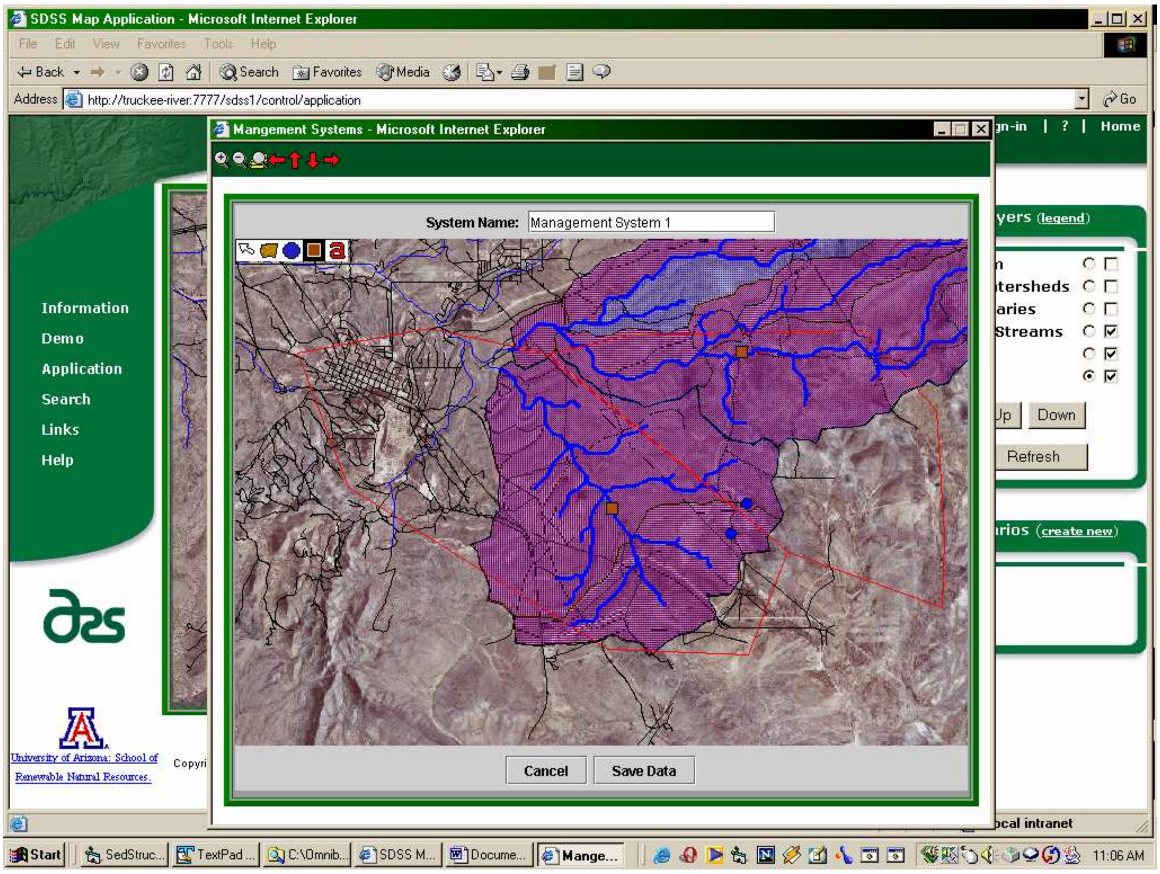


Figure B.4. The user creates a management system by selecting the management system and drawing on the map.

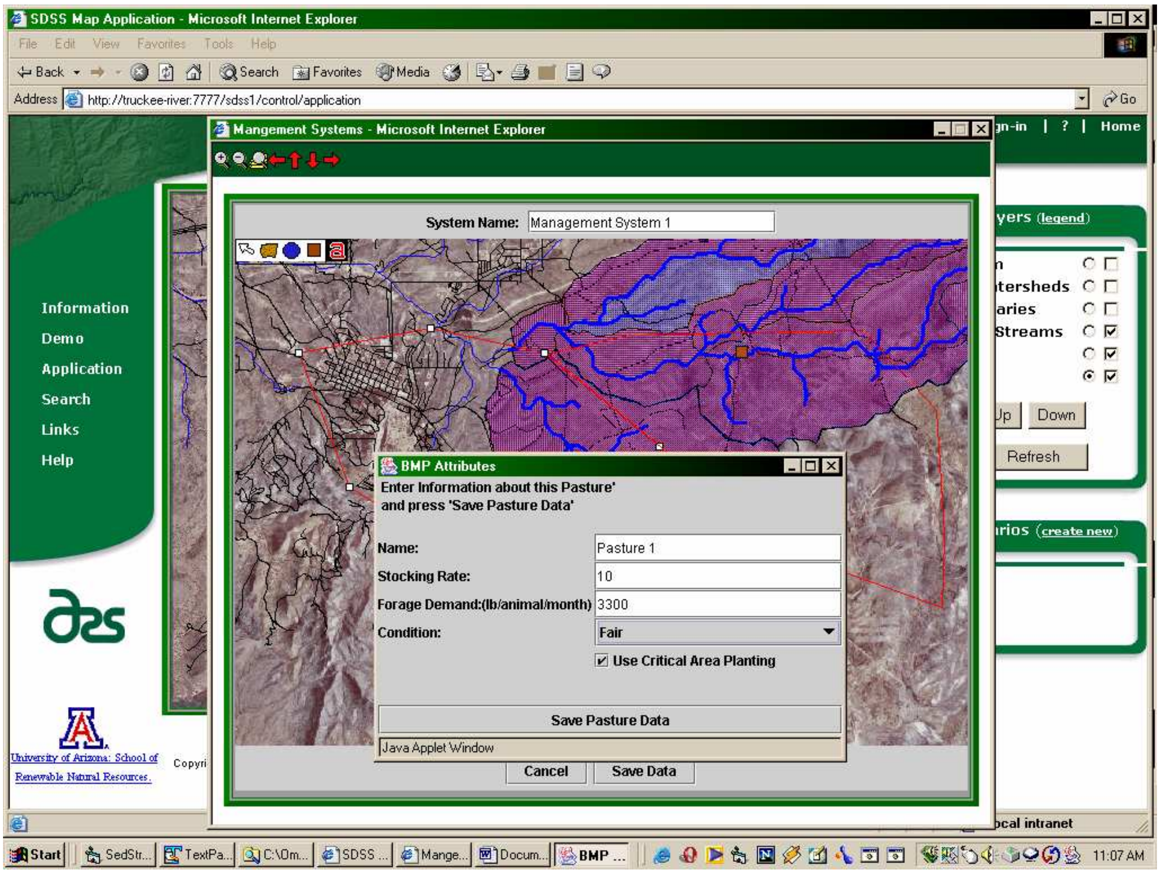


Figure B.5. The user can assign attributes to the management system. For user delineated pastures, users enter the name of the pasture, stocking rate, forage demand, condition, and use of critical area planting.

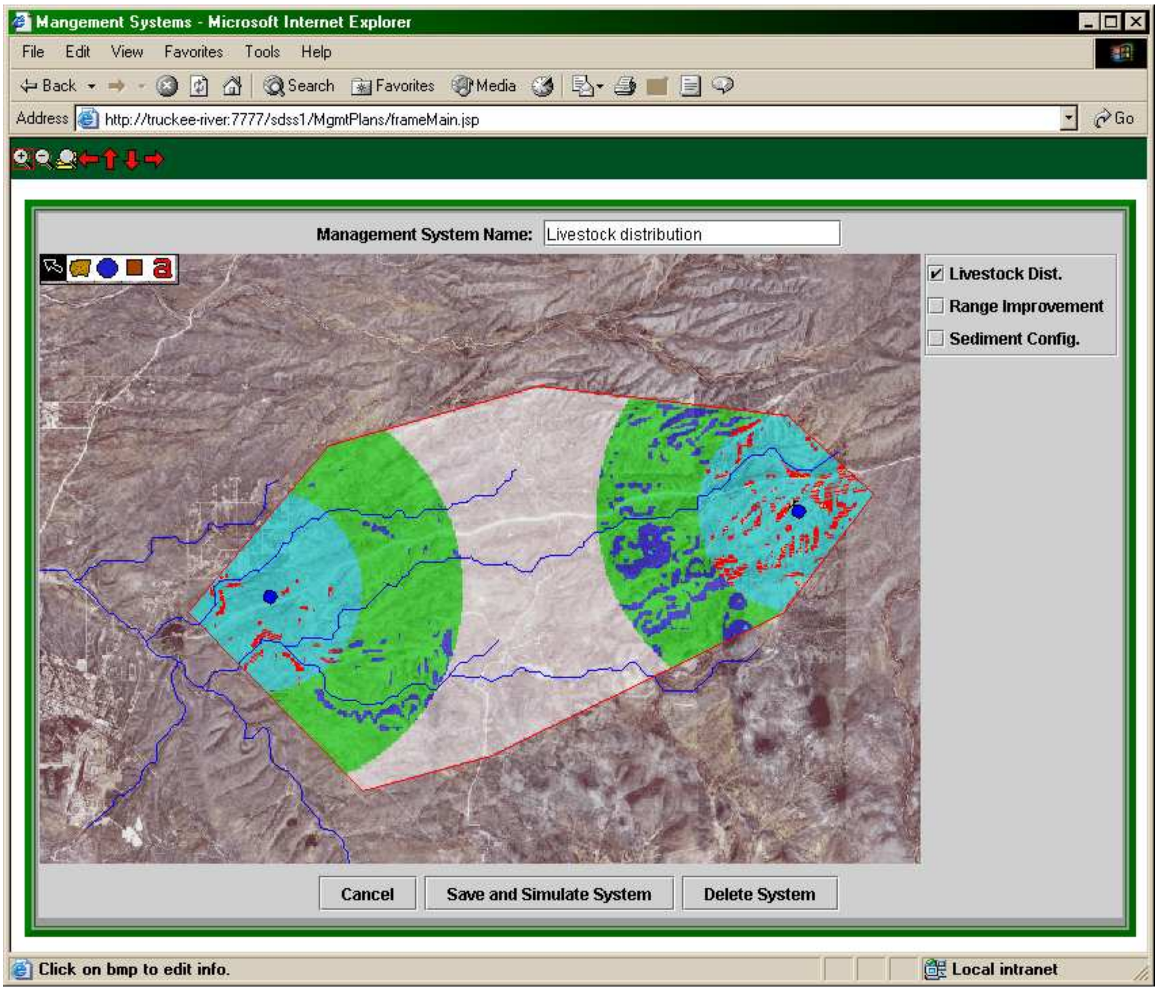


Figure B.6. Simulations are performed for user defined management systems.

Appendix C: KINEROS2 Overview

The model used in this research is KINEROS, version 2, which is a distributed, event-oriented, physically based model that uses the kinematic wave equation to route both runoff and sediment from small agricultural semi-arid or urban watersheds. KINEROS2 represents a watershed through a configuration of a cascade of planes and simulates the hydrologic and hydraulic properties of event-based rainfall, interception, infiltration, Hortionian overland flow, channel routing, and erosion and sediment transport. The channel elements are capable of having two lateral elements and either a channel or an upland element contributing to the channel initiation. A brief description of the hydrologic processes simulated by KINEROS2 is presented in below and additional information can be attained from the KINEROS2 manual (Woolhiser et al., 1990).

Interception

Interception is the rainfall retained on the vegetation surface and is subtracted from the total rainfall available for infiltration. The interception quantity in KINEROS2 is controlled by two input parameters: the interception depth and the portion of the landscape covered by vegetation capable of intercepting precipitation. The total rainfall is reduced by the available interception storage until the total rainfall exceeds the storage capacity.

Infiltration

The infiltration routine in KINEROS2 allows for the characterization and simulation of up to two soils layers and contains multiple parameters that control the infiltration rate. The infiltration capacity during a precipitation event is a function of the total infiltrated depth and the infiltration properties are described by the effective field saturated hydraulic conductivity, the integral capillary drive, and the porosity (Woolhiser et al., 1990). A spatial distribution parameter also represents the natural variability that occurs in the hydraulic parameter. The infiltration capacity is a modification of the Green-Ampt equation that measures the infiltrability as a function of infiltration depth. KINEROS2 also contains methods for calculating infiltration under more complex circumstances, such as for soils with a restrictive upper or lower layer, redistributing soil moisture during a rainfall hiatus and under very wet initial conditions.

Hortonian Overland Flow

Ponding on the soil surface can occur when either the rainfall intensity exceeds the infiltration rate or the soil becomes saturated due to an extensive rain event or an impervious layer underlying the soil surface. KINEROS2 simulates overland flow using a one-dimensional equation with a power relationship that relates water flux to the unit area storage. This power relationship is combined with the continuity equation to formulate kinematic wave equations which are an approximation of the de Saint Venant partial differential equations. The kinematic wave approximation does not simulate wave attenuation but have been found to be an excellent approximation for most overland flow conditions (Woolhiser and Liggett, 1967; Morris and Woolhiser, 1980). The kinematic wave equations are solved using a four-point implicit method and a solution is obtained with a Newton-Raphson numerical method. The resistance of flow provided by the surface can be approximated using a Manning's roughness coefficient, n, or a Chezy friction coefficient, C.

Channel Routing

Unsteady, open channel flow is also simulated using the kinematic wave approximations of the de Saint Venant partial differential equations. Using these assumptions, the continuity equations are re-written so that discharge is a function of cross-sectional channel area. The kinematic equations are also solved using a four point implicit technique similar to the solution for the overland flow component except that the depth of flow is substituted with the cross-sectional area. Water infiltrated into the channel, also referred to as transmission losses, can be simulated in KINEROS2 using the same set of equations used to simulate infiltration in the upland surface.

Erosion and Deposition

KINEROS2 simulates erosion processes by estimating erosion caused by raindrop impact and entrainment by overland flow. Erosion resulting from raindrop impact is approximated as the square of the rainfall intensity and is reduced with increasing depth of water. Erosion caused by entrainment of flow is assumed linearly dependent on the difference between the transport capacity and the current sediment concentration where transport capacity is calculated using a unit stream power approach. Rain splash erosion and transport capacity calculations are performed for each time step and for up to five soil particle sizes and is solved applying a four point finite difference scheme. Channel erosion and sediment transport is estimated using the same approach except that erosion caused by raindrop impact is ignored.

Appendix D: SDSS Data Dictionary

DESIGNSTORM	
Stores the design storm events used in the simulations. This table is the parent table for the designstormvalue table	
Attribute Name	**Description**
STORMID	Unique number identifying the storm event
RETURNPERIOD_YR	The return period of the storm event in years
DURATION	The duration of the storm event in minutes

DESIGNSTORMVALUE	
Stores values for a design storm	
Attribute Name	**Description**
STORMVALID	Unique number identifying the storm value
TIME_MIN	The time the value was measured/derived after the beginning of the storm
INTENSITY	The intensity value in mm/hr for the storm event
DESIGNSTORMID	The design storm associated with this tuple

ELEMENT_OUTPUT	
Simulation model output for a single element	
Attribute Name	**Description**
SIMID	Unique number identifying the element output value
ELEMENTID	The element output id corresponding with this record
TYPE	The type of element (i.e. plane, channel, etc.)
PARAMCODE	A code defining the output parameter value
PARAMNAME	The common name for the parameter name
VALUE	Value of the output
UNITS	the units of the output

LANDCOVERLAYERS	
The land cover data layers stored in the database	
Attribute Name	**Description**
LANDCOVLAYERID	Unique number identifying the land cover layer
NAME	The name of the land cover data layer
SDENAME	The full ArcSDE name of the land cover data layer
DESCRIPTION	A description of the landcover data layer
NUMVEGCLASSES	Number of vegetation classes in the data layer

LANDCOVPARAMETERS	
Modeling parameters that are derived from land cover GIS data layers	
Attribute Name	**Description**
LCPARAMID	Unique number identifying the land cover parameter
SUBWATERSHEDID	Subwatershed number that this parameter is associated
PARAMETERNAME	Model specific land cover parameter name parameter name (i.e. man, int, etc)
VALUE	Value of the parameter
UNITS	Units of the parameter
LCPARAMETERSETID	Parameter set that this parameter value belongs to

LANDCOVPARAMSETS	
Land cover parameter set for a topographic parameterization	
Attribute Name	**Description**
LCPARAMSETID	Unique number identifying the parameter set
MODELID	Simulation model identifier that this parameterization was performed for
LCLAYERID	Land cover GIS layer id used to derive the model parameters
DESCRIPTION	Description of the parameter set
TOPOPARAMSETID	Topographic parameter set id for which the model parameterization was performed
LANDCOVLUTID	Land cover look up table id used to generate the model parameters

LANDCOV_LUT	
Look-up table that relates land cover vegetation classes to model specific parameters	
Attribute Name	**Description**
LCLUTID	Unique identifier for the veg class/model parameter
CLASS	Name of the vegetation class in the GIS grid or coverage
PARAMNAME	Simulation model parameter name that associated with the veg class
VALUE	Simulation model parameter value
UNITS	Units of the parameter value
LCDESCID	Look-up table description identifier

LANDCOV_LUTDESC	
Description of the land cover lookup table	
Attribute Name	**Description**
LCDESCID	Unique identifier for the landcover lookup table
NAME	Name of the lookup table
MODELID	Simulation model id that the lookup table was created
DESCRIPTION	Description of the lookup table

MANAGEMENT_SYSTEMS	
Contains the management systems created by users	
Attribute Name	**Description**
SYSTEMID	Unique identifier identifying the management system
NAME	User defined name of the management system
USERID	User id who created the management system

MGMTSOILSPARAMETERS	
Contains the soil parameters that were adjusted based on management activity	
Attribute Name	**Description**
MGMTSOILSPARAMID	Unique identifier for the management system
SUBWATERSHEDID	Subwatershed id that has simulation model parameters modified
PARAMETERNAME	Simulation model parameter name that was modified
VALUE	New value of the model parameter
UNITS	Units of the parameter value
MGMTSYSTEMID	Management system this record is associated with

PASSWORD	
Stores user passwords for the sdss	
Attribute Name	**Description**
USERID	Unique identifier for the sdss user
PASSWORD	Password of the sdss user

MGMT_TOPOPO_PARAMSET	
Topographic parameter sets that have management systems created	
Attribute Name	**Description**
MGMTTOPOPARAMSETID	Unique identifier for the management topographic parameter set
TOPOPARAMSETID	Topographic parameter set the management system was parameterized
NAME	Name of the management topographic parameter set
SYSTEMID	Management system used in the topographic parameterization

PASTURE	
Stores information on user delineated pastures	
Attribute Name	**Description**
BMPID	Unique identifier for the pasture
SYSTEMID	Management system the pasture is associated with
NAME	Name of the pasture
CONDITION	Ecological condition of the pasture
STOCKING_RATE	Stocking rate of the pasture
CRITICALPLANT	Presence of critical area planting
FORAGE_DEMAND	Forage demand for livestock in the pasture
SHAPE	Pasture polygon

SEDBASIN	
Stores information on user delineated sediment detention basins	
Attribute Name	**Description**
BMPID	Unique identifier for the sediment detention basin
SYSTEMID	Management system the sediment detention basin is associated with
NAME	Name of the sediment detention basin
DESCRIPTION	Description of the sediment detention basin
SHAPE	Sediment detention basin point

SIMULATIONS	
Stores information on user’s simulations performed by the SDSS	
Attribute Name	**Description**
SIMID	Unique identifier of the simulation
MODELID	Model identifier that performed the simulation
TOPOPARAMSETID	Topographic parameter set used to create simulation model parameter sets
SOILSPARAMSETID	Soil parameter set used to create simulation model parameter sets
LCPARAMSETID	Land cover parameter set used to create simulation model parameter sets
NAME	User defined name of the simulation
DESCRIPTION	User defined description of the simulation

SIMULATION_MODEL	
Stores information on simulation models available to use in the spatial decision support system	
Attribute Name	**Description**
MODELID	Unique identifier for the simulation model
NAME	Name of the simulation model
VERSION	Version of the simulation model

SOILSLAYERS	
Stores soil layers available to perform model parameterization	
Attribute Name	**Description**
SOILSLAYERID	Unique identifier for the soils layer
NAME	Name of the soils layer
SDENAME	ArcSDE name of the soils layer
DESCRIPTION	Description of the soils layer

SOILSPARAMETERS	
Stores the soils parameters used in performing model simulations	
Attribute Name	**Description**
SOILSPARAMID	Unique identifier for the soils parameter
SUBWATERSHEDID	Subwatershed number that this parameter is associated
PARAMETERNAME	Model specific soil parameter name parameter name (i.e. ks, pct sand, etc)
VALUE	Value of the parameter
UNITS	Units of the parameter
SOILSPARMETERSETID	Parameter set that this parameter value belongs

SOILSPARAMSETS	
Soils parameter set for a topographic parameterization	
Attribute Name	**Description**
SOILSPARMSETID	Unique number identifying the parameter set
MODELID	Simulation model identifier that this parameterization was performed
SOILSLAYERID	Soils GIS layer id used to derive the model parameters
DESCRIPTION	Description of the parameter set
TOPOPARAMSETID	Topographic parameter set id for which the model parameterization was performed
SOILSLUTID	Soils look up table id used to generate the model parameters

SOILS_LUT	
Stores the soils specific model parameter values based on soil texture	
Attribute Name	**Description**
SOILSLUTID	Identifier for the soils look up table record
TEXTURE	Soil texture parameter used in soils layer
PARAMNAME	Model specific parameter value name
VALUE	Value of the model parameter
UNITS	Units of the parameter
SOILSDESCID	Soils description associated with this record

SOILS_LUTDESC	
Stores general information about soil derived model parameter values	
Attribute Name	**Description**
SOILSDESCID	Identifier for the soils look up table description record
NAME	User defined name of the look up table
MODELID	Simulation model associated with look up table
DESCRIPTION	User defined description of the look up table

STREAM	
Stores data about the stream networks	
Attribute Name	**Description**
TOPOPARAMSETID	Topographic parameter set for which the stream was created
STREAMNUM	The stream number
STREAM_GEOM	Stream geometry line

STREAMPARAMETERS	
Stores modeling parameters for the stream channels	
Attribute Name	**Description**
STREAMPARAMID	Unique identifier for the stream channel parameter
STREAMNUMBER	Stream channel number
PARAMETERNAME	Model parameter name
VALUE	Model parameter values
UNITS	Units of the model parameter value
TOPOPARAMSETID	Topographic parameter set for which the stream was created

SUBWATERSHEDS	
Stores data on the sub watershed created for model simulations	
Attribute Name	**Description**
TOPOPARAMSETID	Topographic parameter set for which the stream was created
SUBWATERSHEDID	Subwatershed number
GEOMETRY	Subwatershed geometry polygon
AREA	Area of the subwatershed

SUMMARY_OUTPUT	
Stores simulation model output summaries	
Attribute Name	**Description**
SIMID	Simulation output record is associated
PARAMCODE	Model parameter code for the output
PARAMNAME	Model parameter name for the output
VALUE	Value of the output
UNITS	Unit of the model output

TOPOGRAPHYLAYERS	
Stores an index of the topography layers (i.e., DEMs) available to be used in the SDSS	
Attribute Name	**Description**
DEMID	Unique identifier for the topography layer
NAME	Topography layer name
SDENAME	Topography layer name as used by ESRI ArcSDE
RESOLUTION	Resolution of the DEM
DESCRIPTION	Description of the DEM
FLOW_DIR_SDENAME	ArcSDE name of the flow direction layer
FLOW_ACCUM_SDENAME	ArcSDE name of the flow accumulation layer

TOPOPARAMETER	
Stores the topographic parameters used in model simulation	
Attribute Name	**Description**
TOPOPARAMID	Unique identifier for the topographic parameter
PARAMNAME	Model specific parameter name
VALUE	Value of the model parameter
UNITS	Units of the model parameter
TOPOPARAMSETID	Topographic parameter set this record is associated
SUBWSHEDID	Subwatershed this topographic parameter is associated with

TOPOPARAMSET	
Stores general information about the topographic parameter set	
Attribute Name	**Description**
TOPOPARAMSETID	Unique identifier for the topography parameter set
CSA	Contributing source area value used in the watershed delineation
DEMID	Topography layer identifier used in the watershed delineation
MODELID	Simulation model the topographic parameter set was created
WATERSHEDID	Subwatershed containing the topographic parameter set

USERS	
Stores information about users of the spatial decision support system	
Attribute Name	**Description**
USERID	Unique identifier of the sdss user
EMAIL	Electronic mailing address of the user
FIRSTNAME	Fist name of the sdss user
LASTNAME	Last name of the sdss user
STADDRESS1	Street address of the sdss user (part 1)
STADDRESS2	Street address of the sdss user (part 2)
CITY	City of the sdss user’s address
STATE	State of the sdss user’s address
ZIP	Zip code of the sdss user’s address
COUNTRY	Country of the sdss user’s address
PHONE	Phone number of the sdss user

WATERPOINT	
Stores the water point best management practice	
Attribute Name	**Description**
BMPID	Unique identifier for the water point
SYSTEMID	Management system the water point is associated with
NAME	Name of the water point
DESCRIPTION	Description of the water point
SHAPE	Water point point

WATERSHED_BOUNDARY	
Store user’s watershed boundaries created through the sdss	
Attribute Name	**Description**
WATERSHEDID	Unique identifier for the watershed boundary
USERID	Owner of the watershed boundary
NAME	User specified name of the watershed boundary
DESCRIPTION	Description of the watershed boundary
SHAPE	Watershed boundary polygon

Appendix E: SDSS Sequence Diagrams

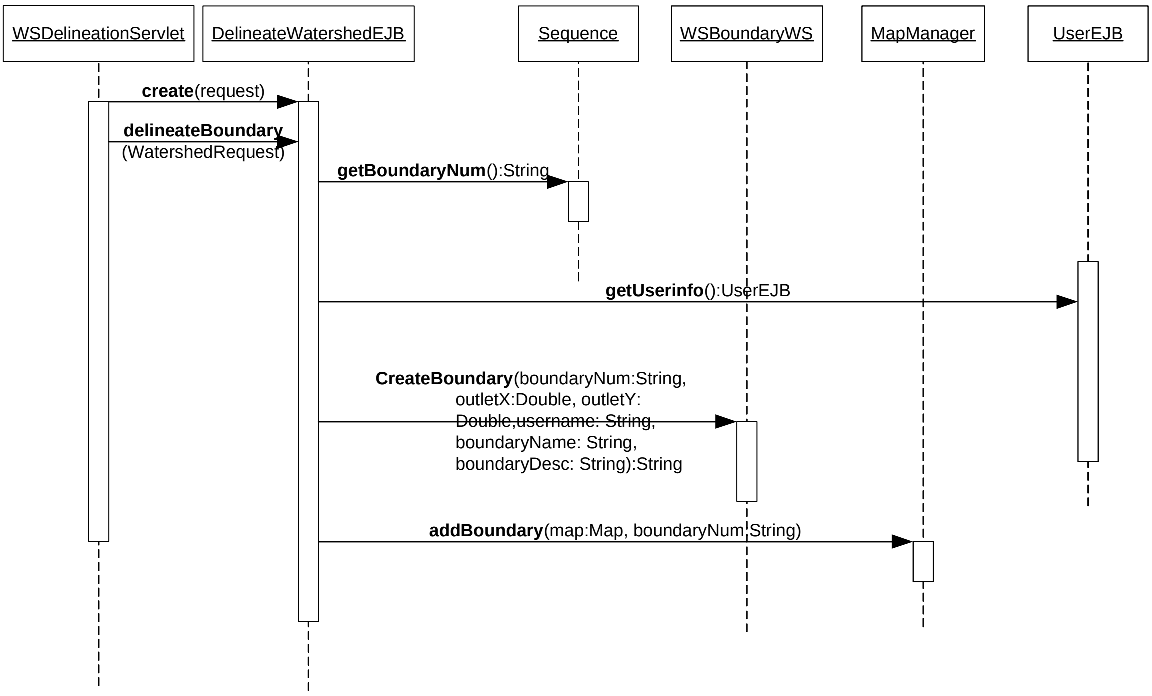


Figure E.1 Delineate Watershed Boundary Use Case

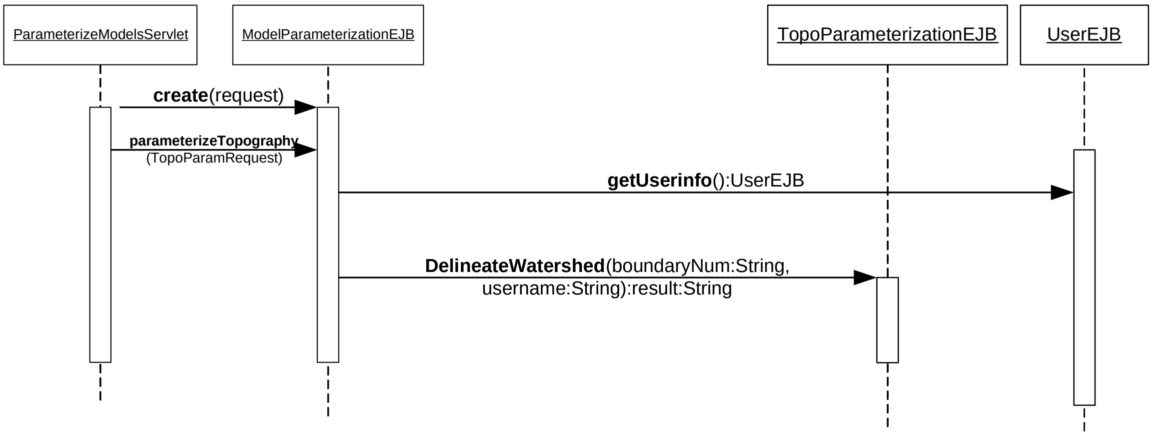


Figure E.2 Topographic Parameterization Use Case

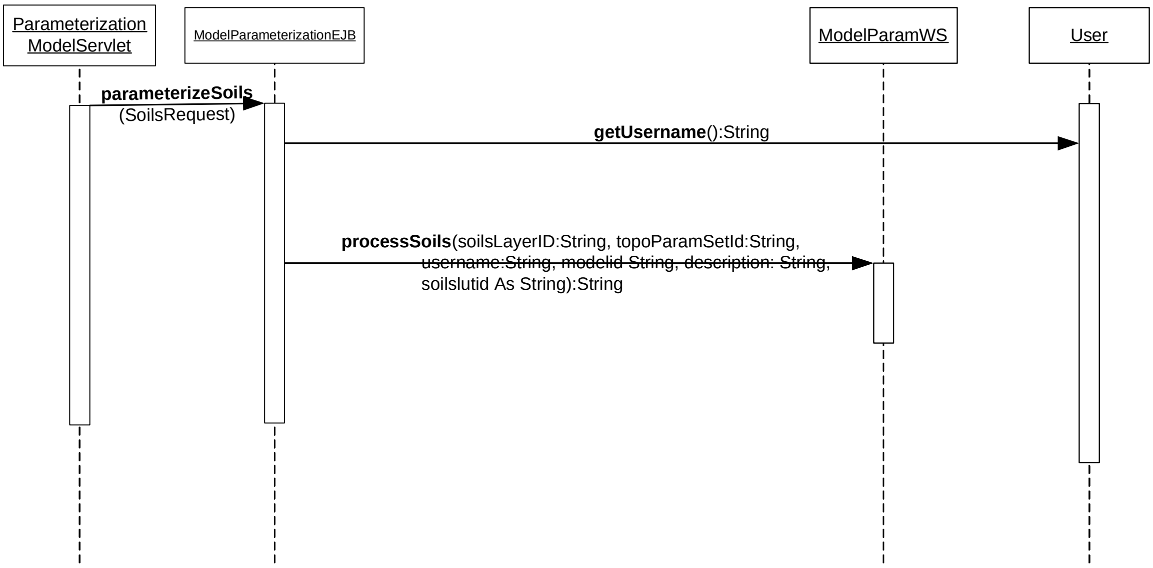


Figure E.3 Soil Parameterization Use Case

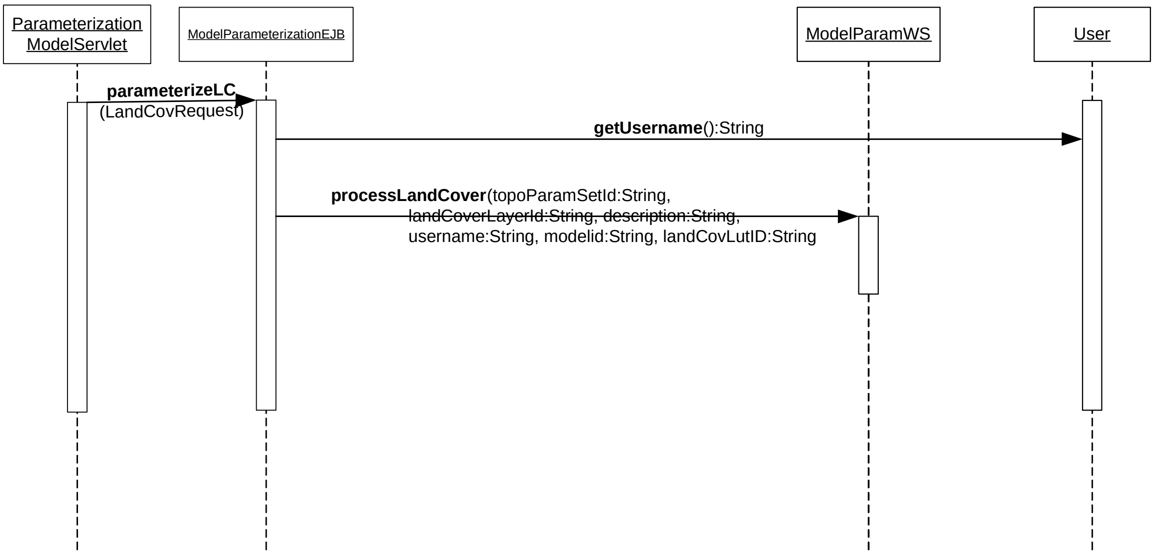


Figure E.4 Land Cover Parameterization Use Case

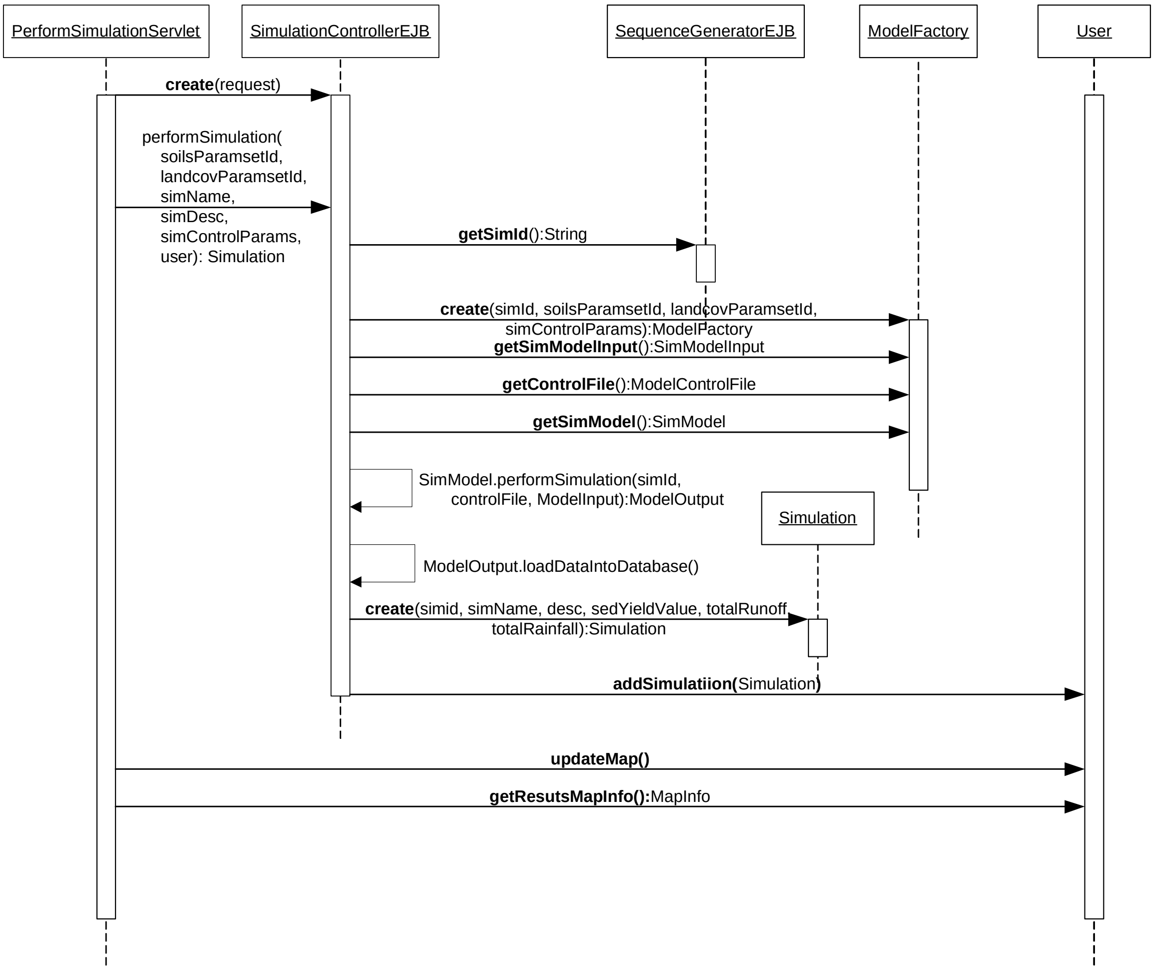


Figure E.5 Perform Hydrologic Simulation Use Case

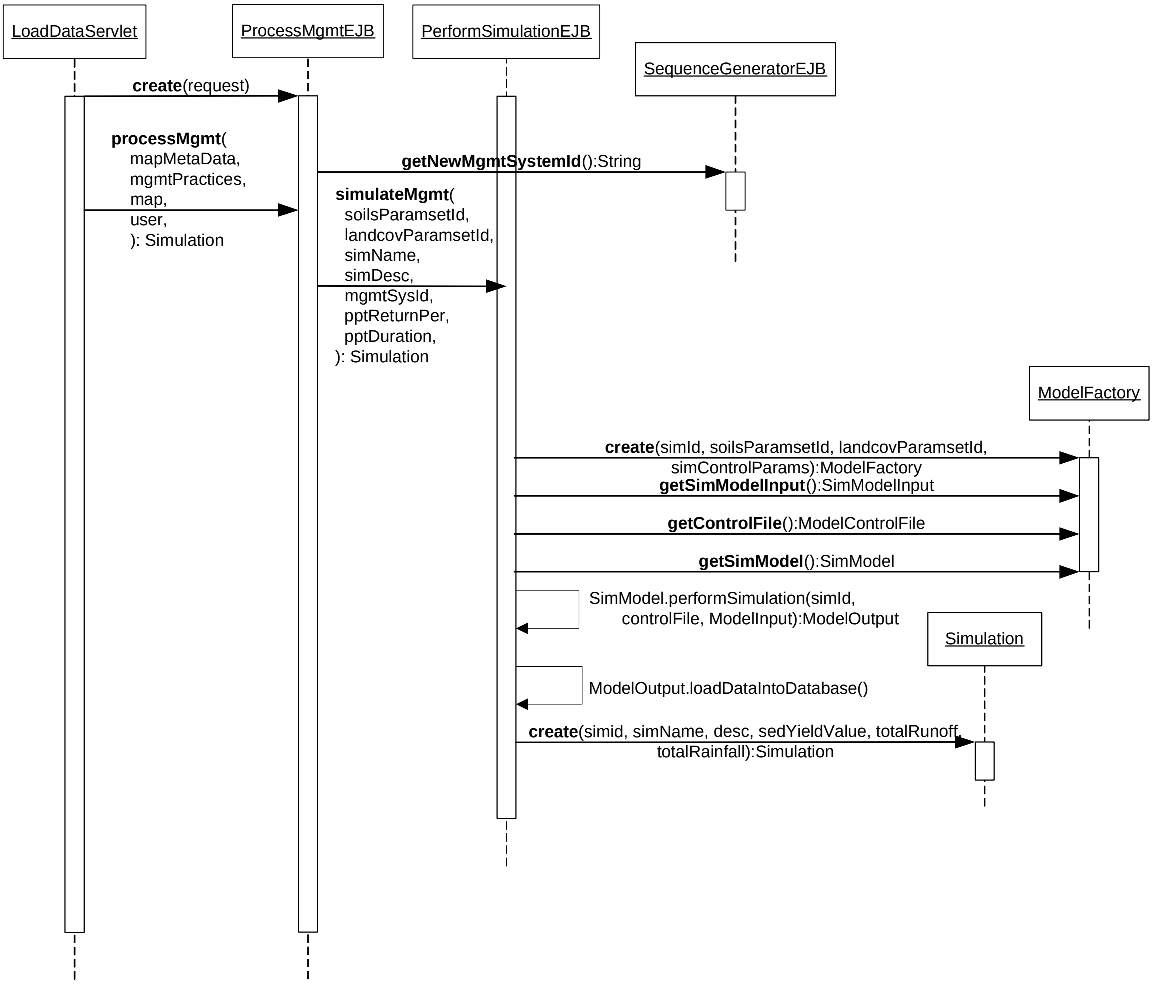


Figure E.6 Perform Management Simulation Use Case

Appendix F: SDSS Methodology for Simulating Range Management Practices

A management system specified by the user can consist of any combination of management practices including sediment detention structures and pasture boundaries. Within each pasture boundary, a management system contains water point locations and attributes associated with the delineated pasture. These attributes include the stocking rate (the number of cattle contained in the pasture), the condition of the allotment (excellent, good, fair, or poor), the type of year which is used to estimate production (favorable, normal, or unfavorable).

User defined parameters for each pasture:

- Stocking Rate: Number of cattle per acre
- Pasture condition: Excellent, Good, Fair, Poor
- Type of year: Favorable, Normal, Unfavorable

SEDIMENT DETENTION STRUCTURES

The location of the sediment detention structure is captured from the user through the application interface and converted to a georeferenced point stored in the database. The contributing area is then computed using a GIS and the contributing area is intersected with the original topographic delineation. The sediment structure contributing area is then removed from the original topographic delineation and the geometric characteristics for the new watershed contributing area are recalculated.

Since the upland and channel elements have been changed from the original model parameterization, the soil and land cover parameterization must be recomputed. However, the interaction with the other management practices must first be determined.

PASTURE MANAGEMENT

The location of water points and pasture boundaries are determined by the user through the interface. The water points and pasture boundaries delineated on the screen are converted to georeferenced features and stored in the database. User defined attributes associated with each pasture include stocking rate and pasture condition; the type of year is stored as an attribute of the management system.

Livestock distribution: The livestock distribution within each pasture is controlled by the location of water sources, topography, and vegetation characteristics. Vegetation characteristics are not currently included in determining livestock distribution, however this information should be included prior to making “real-world” management decisions.

The output from the pasture management is a grid illustrating the relative impact of grazing (ungrazed, light, moderate, and heavy) which is then used in the model parameterization process.

MODEL PARAMETERIZATION

If sediment detention structures are incorporated into the management system, the model parameterization is conducted using the topographic delineation from the sediment routine, otherwise, the original topographic delineation will be used. The soils model parameters values are adjusted based on the grazing impact grid calculated in the pasture management routine specified above. Soils hydraulic conductivity parameters (Ks) are adjusted based on data presented in the literature. The land cover parameters (percent canopy, interception, Manning’s n) should be adjusted using relationships derived from the literature, however, these relationships were not implemented at this time.

To adjust model parameters for management systems without sediment detention structures, the *original* topographic parameter file is converted to a GRID for each hydrologic parameter that is going to be adjusted (Ks for example). This model parameter GRID is then modified based on the relationships between grazing intensity and the parameter. The new adjusted parameter value will be averaged over each topographic element, and the new simulation is conducted. Since the topographic delineation and element characteristics change when sediment detention structures are simulated, the inclusion of sediment detention structures in the modeling process requires an extra step. Prior to converting the element values to a model parameter grid, the sediment detention structure contributing area is removed from the watershed area.

A grazing intensity is classified using the following values:

1 – ungrazed
2 – light grazing intensity
3 – moderate grazing intensity
4 – heavy grazing intensity

RECOMMENDATIONS FOR IMPROVEMENTS:

Recommendations for improving the inclusion of management in the simulations are:

- Include vegetation characteristics in addition to water source distance and topography to predict livestock distribution.
- Include stocking rate and range condition in determining reduction in model parameter values.
- Adjust land cover parameters (interception capacity, percent cover, Manning’s roughness, etc.) based on grazing impact.
- Currently contributing areas to sediment detention structures are removed from the simulation assuming that the structure never overflows. The detention structure could be included in the model as a pond and would overflow and contribute to the downstream channel flow, a more realistic scenario.

Appendix G: KINEROS2 Parameters for Watershed 11

G.1 Default KINEROS2 channel parameters

Parameter Name	Value
MAN	0.035
Wool	Yes
CV	0
DIST	0.545
FR	0.05, 0.05, 0.9
SS1	1
KSAT	210
POR	0.44
SS2	1
G	101
ROCK	0"
SP	63
COH	0.005

G.2 KINEROS2 parameters values derived from NALC imagery

Mesquite Woodlands	
Interception	1.15
Percent Cover	20
Mannings N	0.04
Grasslands	
Interception	2.00
Percent Cover	25
Mannings N	0.05
Desert Scrub	
Interception	3.00
Percent Cover	10
Mannings N	0.055

G.3 KINEROS2 parameters values for Watershed 11 derived from STATSGO soils (Mapping unit AZ061)

Parameter Name	Value
Pave	0
Splash	24.91
Rock	0.43
Ks	6.67
G	114.97
Por	0.459
Smax	0.93
Cv	0.95
Sand	0.5
Silt	0.33
Clay	0.16
Dist	0.3
Cohesion	0.006

Appendix H: Chapter 5 Simulation Results

Table H.1 Simulated runoff volume

DEM	Contributing Source Area (%)	PPT Event Date	Simulated RO Vol (mm)	Observed RO Vol (mm)
SAR 2.5M	1.5	08/25/84	0.41	0.38
SAR 2.5M	1.5	07/17/85	6.97	1.66
SAR 2.5M	1.5	06/24/86	1.20	0.38
SAR 2.5M	1.5	07/15/86	0.76	0.40
SAR 2.5M	1.5	08/09/86	11.53	2.72
SAR 2.5M	1.5	08/10/86	0.00	0.78
SAR 2.5M	1.5	08/14/86	1.72	2.45
SAR 2.5M	1.5	08/17/86	1.32	2.89
SAR 2.5M	1.5	08/29/86	7.83	7.82
SAR 2.5M	1.5	08/03/88	0.06	2.00
SAR 2.5M	1.5	08/20/88	0.15	0.62
SAR 2.5M	8	08/25/84	0.12	0.38
SAR 2.5M	8	07/17/85	4.50	1.66
SAR 2.5M	8	06/24/86	0.58	0.38
SAR 2.5M	8	07/15/86	0.33	0.40
SAR 2.5M	8	08/09/86	8.62	2.72
SAR 2.5M	8	08/10/86	0.00	0.78
SAR 2.5M	8	08/14/86	0.89	2.45
SAR 2.5M	8	08/17/86	0.60	2.89
SAR 2.5M	8	08/29/86	4.96	7.82
SAR 2.5M	8	08/03/88	0.02	2.00
SAR 2.5M	8	08/20/88	0.08	0.62
SAR 2.5M	15	08/25/84	0.09	0.38
SAR 2.5M	15	07/17/85	3.82	1.66
SAR 2.5M	15	06/24/86	0.45	0.38
SAR 2.5M	15	07/15/86	0.21	0.40
SAR 2.5M	15	08/09/86	7.73	2.72
SAR 2.5M	15	08/10/86	0.00	0.78
SAR 2.5M	15	08/14/86	0.69	2.45
SAR 2.5M	15	08/17/86	0.37	2.89
SAR 2.5M	15	08/29/86	4.29	7.82
SAR 2.5M	15	08/03/88	0.05	2.00
SAR 2.5M	15	08/20/88	0.06	0.62
SAR 10M	1.5	08/25/84	0.27	0.38
SAR 10M	1.5	07/17/85	6.34	1.66
SAR 10M	1.5	06/24/86	0.92	0.38
SAR 10M	1.5	07/15/86	0.54	0.40
SAR 10M	1.5	08/09/86	11.01	2.72

SAR 10M	1.5	08/10/86	0.00	0.78
SAR 10M	1.5	08/14/86	1.37	2.45
SAR 10M	1.5	08/17/86	0.96	2.89
SAR 10M	1.5	08/29/86	7.13	7.82
SAR 10M	1.5	08/03/88	0.03	2.00
SAR 10M	1.5	08/20/88	0.11	0.62
SAR 10M	8	08/25/84	0.10	0.38
SAR 10M	8	07/17/85	3.92	1.66
SAR 10M	8	06/24/86	0.47	0.38
SAR 10M	8	07/15/86	0.24	0.40
SAR 10M	8	08/09/86	7.77	2.72
SAR 10M	8	08/10/86	0.00	0.78
SAR 10M	8	08/14/86	0.73	2.45
SAR 10M	8	08/17/86	0.48	2.89
SAR 10M	8	08/29/86	4.32	7.82
SAR 10M	8	08/03/88	0.01	2.00
SAR 10M	8	08/20/88	0.06	0.62
SAR 10M	15	08/25/84	0.10	0.38
SAR 10M	15	07/17/85	3.20	1.66
SAR 10M	15	06/24/86	0.35	0.38
SAR 10M	15	07/15/86	0.18	0.40
SAR 10M	15	08/09/86	6.81	2.72
SAR 10M	15	08/10/86	0.00	0.78
SAR 10M	15	08/14/86	0.58	2.45
SAR 10M	15	08/17/86	0.29	2.89
SAR 10M	15	08/29/86	3.64	7.82
SAR 10M	15	08/03/88	0.03	2.00
SAR 10M	15	08/20/88	0.05	0.62
USGS 10M	1.5	08/25/84	0.18	0.38
USGS 10M	1.5	07/17/85	6.10	1.66
USGS 10M	1.5	06/24/86	0.77	0.38
USGS 10M	1.5	07/15/86	0.44	0.40
USGS 10M	1.5	08/09/86	10.79	2.72
USGS 10M	1.5	08/10/86	0.00	0.78
USGS 10M	1.5	08/14/86	1.19	2.45
USGS 10M	1.5	08/17/86	0.81	2.89
USGS 10M	1.5	08/29/86	6.88	7.82
USGS 10M	1.5	08/03/88	0.03	2.00
USGS 10M	1.5	08/20/88	0.08	0.62
USGS 10M	8	08/25/84	0.07	0.38
USGS 10M	8	07/17/85	3.10	1.66
USGS 10M	8	06/24/86	0.36	0.38
USGS 10M	8	07/15/86	0.18	0.40
USGS 10M	8	08/09/86	6.80	2.72
USGS 10M	8	08/10/86	0.00	0.78
USGS 10M	8	08/14/86	0.57	2.45
USGS 10M	8	08/17/86	0.35	2.89

USGS 10M	8	08/29/86	3.69	7.82
USGS 10M	8	08/03/88	0.01	2.00
USGS 10M	8	08/20/88	0.04	0.62
USGS 10M	15	08/25/84	0.06	0.38
USGS 10M	15	07/17/85	2.58	1.66
USGS 10M	15	06/24/86	0.26	0.38
USGS 10M	15	07/15/86	0.13	0.40
USGS 10M	15	08/09/86	5.59	2.72
USGS 10M	15	08/10/86	0.00	0.78
USGS 10M	15	08/14/86	0.44	2.45
USGS 10M	15	08/17/86	0.21	2.89
USGS 10M	15	08/29/86	2.93	7.82
USGS 10M	15	08/03/88	0.02	2.00
USGS 10M	15	08/20/88	0.04	0.62
USGS 30M	1.5	08/25/84	0.27	0.38
USGS 30M	1.5	07/17/85	6.25	1.66
USGS 30M	1.5	06/24/86	0.88	0.38
USGS 30M	1.5	07/15/86	0.52	0.40
USGS 30M	1.5	08/09/86	10.91	2.72
USGS 30M	1.5	08/10/86	0.00	0.78
USGS 30M	1.5	08/14/86	1.36	2.45
USGS 30M	1.5	08/17/86	0.91	2.89
USGS 30M	1.5	08/29/86	7.03	7.82
USGS 30M	1.5	08/03/88	0.02	2.00
USGS 30M	1.5	08/20/88	0.09	0.62
USGS 30M	8	08/25/84	0.06	0.38
USGS 30M	8	07/17/85	2.96	1.66
USGS 30M	8	06/24/86	0.34	0.38
USGS 30M	8	07/15/86	0.18	0.40
USGS 30M	8	08/09/86	6.54	2.72
USGS 30M	8	08/10/86	0.00	0.78
USGS 30M	8	08/14/86	0.54	2.45
USGS 30M	8	08/17/86	0.33	2.89
USGS 30M	8	08/29/86	3.53	7.82
USGS 30M	8	08/03/88	0.01	2.00
USGS 30M	8	08/20/88	0.04	0.62
USGS 30M	15	08/25/84	0.06	0.38
USGS 30M	15	07/17/85	2.44	1.66
USGS 30M	15	06/24/86	0.25	0.38
USGS 30M	15	07/15/86	0.13	0.40
USGS 30M	15	08/09/86	5.30	2.72
USGS 30M	15	08/10/86	0.00	0.78
USGS 30M	15	08/14/86	0.42	2.45
USGS 30M	15	08/17/86	0.20	2.89
USGS 30M	15	08/29/86	2.77	7.82
USGS 30M	15	08/03/88	0.02	2.00
USGS 30M	15	08/20/88	0.04	0.62

WG 10M	1.5	08/25/84	0.25	0.38
WG 10M	1.5	07/17/85	6.21	1.66
WG 10M	1.5	06/24/86	0.87	0.38
WG 10M	1.5	07/15/86	0.52	0.40
WG 10M	1.5	08/09/86	10.87	2.72
WG 10M	1.5	08/10/86	0.00	0.78
WG 10M	1.5	08/14/86	1.33	2.45
WG 10M	1.5	08/17/86	0.91	2.89
WG 10M	1.5	08/29/86	7.01	7.82
WG 10M	1.5	08/03/88	0.03	2.00
WG 10M	1.5	08/20/88	0.10	0.62
WG 10M	8	08/25/84	0.08	0.38
WG 10M	8	07/17/85	3.75	1.66
WG 10M	8	06/24/86	0.43	0.38
WG 10M	8	07/15/86	0.23	0.40
WG 10M	8	08/09/86	7.47	2.72
WG 10M	8	08/10/86	0.00	0.78
WG 10M	8	08/14/86	0.69	2.45
WG 10M	8	08/17/86	0.43	2.89
WG 10M	8	08/29/86	4.15	7.82
WG 10M	8	08/03/88	0.02	2.00
WG 10M	8	08/20/88	0.06	0.62
WG 10M	15	08/25/84	0.07	0.38
WG 10M	15	07/17/85	3.03	1.66
WG 10M	15	06/24/86	0.32	0.38
WG 10M	15	07/15/86	0.17	0.40
WG 10M	15	08/09/86	6.48	2.72
WG 10M	15	08/10/86	0.00	0.78
WG 10M	15	08/14/86	0.54	2.45
WG 10M	15	08/17/86	0.27	2.89
WG 10M	15	08/29/86	3.47	7.82
WG 10M	15	08/03/88	0.03	2.00
WG 10M	15	08/20/88	0.04	0.62
SRTM 90M	8	08/25/84	0.06	0.38
SRTM 90M	8	07/17/85	2.52	1.66
SRTM 90M	8	06/24/86	0.27	0.38
SRTM 90M	8	07/15/86	0.16	0.40
SRTM 90M	8	08/09/86	5.58	2.72
SRTM 90M	8	08/10/86	0.00	0.78
SRTM 90M	8	08/14/86	0.47	2.45
SRTM 90M	8	08/17/86	0.30	2.89
SRTM 90M	8	08/29/86	2.89	7.82
SRTM 90M	8	08/03/88	0.01	2.00
SRTM 90M	8	08/20/88	0.04	0.62
SRTM 90M	15	08/25/84	0.06	0.38
SRTM 90M	15	07/17/85	2.00	1.66
SRTM 90M	15	06/24/86	0.20	0.38

SRTM 90M	15	07/15/86	0.12	0.40
SRTM 90M	15	08/09/86	4.26	2.72
SRTM 90M	15	08/10/86	0.00	0.78
SRTM 90M	15	08/14/86	0.36	2.45
SRTM 90M	15	08/17/86	0.20	2.89
SRTM 90M	15	08/29/86	2.32	7.82
SRTM 90M	15	08/03/88	0.01	2.00
SRTM 90M	15	08/20/88	0.03	0.62

Table H.2 Simulated peak runoff

DEM	Contributing Source Area (%)	PPT Event Date	Simulated Peak Q (mm/hr)	Observed Peak RO (mm/hr)
SAR 2.5M	1.5	8/25/1984	0.58	0.70
SAR 2.5M	1.5	7/17/1985	8.97	3.46
SAR 2.5M	1.5	6/24/1986	1.91	0.59
SAR 2.5M	1.5	7/15/1986	1.03	0.67
SAR 2.5M	1.5	8/9/1986	15.66	4.47
SAR 2.5M	1.5	8/10/1986	0.00	2.55
SAR 2.5M	1.5	8/14/1986	2.64	3.06
SAR 2.5M	1.5	8/17/1986	1.16	3.31
SAR 2.5M	1.5	8/29/1986	10.54	8.84
SAR 2.5M	1.5	8/3/1988	0.09	3.13
SAR 2.5M	1.5	8/20/1988	0.29	0.69
SAR 2.5M	8.0	8/25/1984	0.15	0.70
SAR 2.5M	8.0	7/17/1985	4.48	3.46
SAR 2.5M	8.0	6/24/1986	0.83	0.59
SAR 2.5M	8.0	7/15/1986	0.44	0.67
SAR 2.5M	8.0	8/9/1986	7.98	4.47
SAR 2.5M	8.0	8/10/1986	0.00	2.55
SAR 2.5M	8.0	8/14/1986	1.17	3.06
SAR 2.5M	8.0	8/17/1986	0.48	3.31
SAR 2.5M	8.0	8/29/1986	5.15	8.84
SAR 2.5M	8.0	8/3/1988	0.03	3.13
SAR 2.5M	8.0	8/20/1988	0.15	0.69
SAR 2.5M	15.0	8/25/1984	0.13	0.70
SAR 2.5M	15.0	7/17/1985	3.44	3.46
SAR 2.5M	15.0	6/24/1986	0.70	0.59
SAR 2.5M	15.0	7/15/1986	0.27	0.67
SAR 2.5M	15.0	8/9/1986	5.98	4.47
SAR 2.5M	15.0	8/10/1986	0.00	2.55
SAR 2.5M	15.0	8/14/1986	0.94	3.06
SAR 2.5M	15.0	8/17/1986	0.36	3.31
SAR 2.5M	15.0	8/29/1986	4.20	8.84
SAR 2.5M	15.0	8/3/1988	0.10	3.13

SAR 2.5M	15.0	8/20/1988	0.09	0.69
SAR 10M	1.5	8/25/1984	0.37	0.70
SAR 10M	1.5	7/17/1985	7.58	3.46
SAR 10M	1.5	6/24/1986	1.35	0.59
SAR 10M	1.5	7/15/1986	0.72	0.67
SAR 10M	1.5	8/9/1986	13.45	4.47
SAR 10M	1.5	8/10/1986	0.00	2.55
SAR 10M	1.5	8/14/1986	1.96	3.06
SAR 10M	1.5	8/17/1986	0.81	3.31
SAR 10M	1.5	8/29/1986	8.73	8.84
SAR 10M	1.5	8/3/1988	0.05	3.13
SAR 10M	1.5	8/20/1988	0.16	0.69
SAR 10M	8.0	8/25/1984	0.13	0.70
SAR 10M	8.0	7/17/1985	3.80	3.46
SAR 10M	8.0	6/24/1986	0.63	0.59
SAR 10M	8.0	7/15/1986	0.31	0.67
SAR 10M	8.0	8/9/1986	6.89	4.47
SAR 10M	8.0	8/10/1986	0.00	2.55
SAR 10M	8.0	8/14/1986	0.93	3.06
SAR 10M	8.0	8/17/1986	0.39	3.31
SAR 10M	8.0	8/29/1986	4.27	8.84
SAR 10M	8.0	8/3/1988	0.01	3.13
SAR 10M	8.0	8/20/1988	0.11	0.69
SAR 10M	15.0	8/25/1984	0.14	0.70
SAR 10M	15.0	7/17/1985	2.98	3.46
SAR 10M	15.0	6/24/1986	0.52	0.59
SAR 10M	15.0	7/15/1986	0.23	0.67
SAR 10M	15.0	8/9/1986	5.26	4.47
SAR 10M	15.0	8/10/1986	0.00	2.55
SAR 10M	15.0	8/14/1986	0.75	3.06
SAR 10M	15.0	8/17/1986	0.29	3.31
SAR 10M	15.0	8/29/1986	3.58	8.84
SAR 10M	15.0	8/3/1988	0.04	3.13
SAR 10M	15.0	8/20/1988	0.06	0.69
USGS 10M	1.5	8/25/1984	0.21	0.70
USGS 10M	1.5	7/17/1985	6.98	3.46
USGS 10M	1.5	6/24/1986	1.11	0.59
USGS 10M	1.5	7/15/1986	0.58	0.67
USGS 10M	1.5	8/9/1986	12.36	4.47
USGS 10M	1.5	8/10/1986	0.00	2.55
USGS 10M	1.5	8/14/1986	1.71	3.06
USGS 10M	1.5	8/17/1986	0.69	3.31
USGS 10M	1.5	8/29/1986	8.02	8.84
USGS 10M	1.5	8/3/1988	0.06	3.13
USGS 10M	1.5	8/20/1988	0.10	0.69
USGS 10M	8.0	8/25/1984	0.09	0.70
USGS 10M	8.0	7/17/1985	3.10	3.46

USGS 10M	8.0	6/24/1986	0.43	0.59
USGS 10M	8.0	7/15/1986	0.22	0.67
USGS 10M	8.0	8/9/1986	5.78	4.47
USGS 10M	8.0	8/10/1986	0.00	2.55
USGS 10M	8.0	8/14/1986	0.71	3.06
USGS 10M	8.0	8/17/1986	0.28	3.31
USGS 10M	8.0	8/29/1986	3.59	8.84
USGS 10M	8.0	8/3/1988	0.02	3.13
USGS 10M	8.0	8/20/1988	0.07	0.69
USGS 10M	15.0	8/25/1984	0.09	0.70
USGS 10M	15.0	7/17/1985	2.32	3.46
USGS 10M	15.0	6/24/1986	0.38	0.59
USGS 10M	15.0	7/15/1986	0.16	0.67
USGS 10M	15.0	8/9/1986	4.10	4.47
USGS 10M	15.0	8/10/1986	0.00	2.55
USGS 10M	15.0	8/14/1986	0.56	3.06
USGS 10M	15.0	8/17/1986	0.22	3.31
USGS 10M	15.0	8/29/1986	2.75	8.84
USGS 10M	15.0	8/3/1988	0.02	3.13
USGS 10M	15.0	8/20/1988	0.04	0.69
USGS 30M	1.5	8/25/1984	0.34	0.70
USGS 30M	1.5	7/17/1985	7.76	3.46
USGS 30M	1.5	6/24/1986	1.34	0.59
USGS 30M	1.5	7/15/1986	0.69	0.67
USGS 30M	1.5	8/9/1986	13.83	4.47
USGS 30M	1.5	8/10/1986	0.00	2.55
USGS 30M	1.5	8/14/1986	2.03	3.06
USGS 30M	1.5	8/17/1986	0.80	3.31
USGS 30M	1.5	8/29/1986	8.92	8.84
USGS 30M	1.5	8/3/1988	0.03	3.13
USGS 30M	1.5	8/20/1988	0.12	0.69
USGS 30M	8.0	8/25/1984	0.08	0.70
USGS 30M	8.0	7/17/1985	2.87	3.46
USGS 30M	8.0	6/24/1986	0.44	0.59
USGS 30M	8.0	7/15/1986	0.22	0.67
USGS 30M	8.0	8/9/1986	5.45	4.47
USGS 30M	8.0	8/10/1986	0.00	2.55
USGS 30M	8.0	8/14/1986	0.69	3.06
USGS 30M	8.0	8/17/1986	0.28	3.31
USGS 30M	8.0	8/29/1986	3.27	8.84
USGS 30M	8.0	8/3/1988	0.01	3.13
USGS 30M	8.0	8/20/1988	0.06	0.69
USGS 30M	15.0	8/25/1984	0.09	0.70
USGS 30M	15.0	7/17/1985	2.16	3.46
USGS 30M	15.0	6/24/1986	0.36	0.59
USGS 30M	15.0	7/15/1986	0.16	0.67
USGS 30M	15.0	8/9/1986	3.86	4.47

USGS 30M	15.0	8/10/1986	0.00	2.55
USGS 30M	15.0	8/14/1986	0.53	3.06
USGS 30M	15.0	8/17/1986	0.21	3.31
USGS 30M	15.0	8/29/1986	2.53	8.84
USGS 30M	15.0	8/3/1988	0.02	3.13
USGS 30M	15.0	8/20/1988	0.04	0.69
WG 10M	1.5	8/25/1984	0.33	0.70
WG 10M	1.5	7/17/1985	7.41	3.46
WG 10M	1.5	6/24/1986	1.32	0.59
WG 10M	1.5	7/15/1986	0.69	0.67
WG 10M	1.5	8/9/1986	13.11	4.47
WG 10M	1.5	8/10/1986	0.00	2.55
WG 10M	1.5	8/14/1986	1.95	3.06
WG 10M	1.5	8/17/1986	0.78	3.31
WG 10M	1.5	8/29/1986	8.62	8.84
WG 10M	1.5	8/3/1988	0.06	3.13
WG 10M	1.5	8/20/1988	0.14	0.69
WG 10M	8.0	8/25/1984	0.09	0.70
WG 10M	8.0	7/17/1985	3.66	3.46
WG 10M	8.0	6/24/1986	0.58	0.59
WG 10M	8.0	7/15/1986	0.29	0.67
WG 10M	8.0	8/9/1986	6.63	4.47
WG 10M	8.0	8/10/1986	0.00	2.55
WG 10M	8.0	8/14/1986	0.88	3.06
WG 10M	8.0	8/17/1986	0.35	3.31
WG 10M	8.0	8/29/1986	4.15	8.84
WG 10M	8.0	8/3/1988	0.02	3.13
WG 10M	8.0	8/20/1988	0.10	0.69
WG 10M	15.0	8/25/1984	0.10	0.70
WG 10M	15.0	7/17/1985	2.86	3.46
WG 10M	15.0	6/24/1986	0.48	0.59
WG 10M	15.0	7/15/1986	0.21	0.67
WG 10M	15.0	8/9/1986	5.04	4.47
WG 10M	15.0	8/10/1986	0.00	2.55
WG 10M	15.0	8/14/1986	0.69	3.06
WG 10M	15.0	8/17/1986	0.27	3.31
WG 10M	15.0	8/29/1986	3.46	8.84
WG 10M	15.0	8/3/1988	0.04	3.13
WG 10M	15.0	8/20/1988	0.05	0.69
SRTM 90M	8.0	8/25/1984	0.08	0.70
SRTM 90M	8.0	7/17/1985	2.43	3.46
SRTM 90M	8.0	6/24/1986	0.35	0.59
SRTM 90M	8.0	7/15/1986	0.18	0.67
SRTM 90M	8.0	8/9/1986	4.63	4.47
SRTM 90M	8.0	8/10/1986	0.00	2.55
SRTM 90M	8.0	8/14/1986	0.58	3.06
SRTM 90M	8.0	8/17/1986	0.23	3.31

SRTM 90M	8.0	8/29/1986	2.80	8.84
SRTM 90M	8.0	8/3/1988	0.01	3.13
SRTM 90M	8.0	8/20/1988	0.05	0.69
SRTM 90M	15.0	8/25/1984	0.07	0.70
SRTM 90M	15.0	7/17/1985	1.85	3.46
SRTM 90M	15.0	6/24/1986	0.29	0.59
SRTM 90M	15.0	7/15/1986	0.15	0.67
SRTM 90M	15.0	8/9/1986	3.34	4.47
SRTM 90M	15.0	8/10/1986	0.00	2.55
SRTM 90M	15.0	8/14/1986	0.46	3.06
SRTM 90M	15.0	8/17/1986	0.19	3.31
SRTM 90M	15.0	8/29/1986	2.22	8.84
SRTM 90M	15.0	8/3/1988	0.02	3.13
SRTM 90M	15.0	8/20/1988	0.04	0.69

Appendix I: Chapter 6 Simulation Results

Table I.1. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 1.5% contributing source area and a 5 year return period, 30 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 6	2.339	tons/ha	1
IFSAR 2.5M	Management System 2	2.730	tons/ha	2
IFSAR 2.5M	Management System 3	3.414	tons/ha	3
IFSAR 2.5M	Management System 4	3.591	tons/ha	4
IFSAR 2.5M	Management System 1	3.673	tons/ha	5
IFSAR 2.5M	Management System 5	3.760	tons/ha	6
IFSAR 10M	Management System 1	0.535	tons/ha	1
IFSAR 10M	Management System 6	0.649	tons/ha	2
IFSAR 10M	Management System 3	0.821	tons/ha	3
IFSAR 10M	Management System 5	0.830	tons/ha	4
IFSAR 10M	Management System 2	0.853	tons/ha	5
IFSAR 10M	Management System 4	0.976	tons/ha	6
USGS 10M	Management System 6	0.205	tons/ha	1
USGS 10M	Management System 2	0.270	tons/ha	2
USGS 10M	Management System 4	0.325	tons/ha	3
USGS 10M	Management System 1	0.353	tons/ha	4
USGS 10M	Management System 3	0.402	tons/ha	5
USGS 10M	Management System 5	0.437	tons/ha	6
USGS 30M	Management System 6	0.151	tons/ha	1
USGS 30M	Management System 1	0.320	tons/ha	2
USGS 30M	Management System 5	0.335	tons/ha	3
USGS 30M	Management System 3	0.373	tons/ha	4
USGS 30M	Management System 4	0.403	tons/ha	5
USGS 30M	Management System 2	0.618	tons/ha	6
WG 10M	Management System 6	0.408	tons/ha	1
WG 10M	Management System 1	0.586	tons/ha	2
WG 10M	Management System 2	0.594	tons/ha	3
WG 10M	Management System 4	0.763	tons/ha	4
WG 10M	Management System 3	0.777	tons/ha	5
WG 10M	Management System 5	0.789	tons/ha	6

Table I.2. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 1.5% contributing source area and a 5 year return period, 60 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 6	6.697	tons/ha	1
IFSAR 2.5M	Management System 2	7.691	tons/ha	2
IFSAR 2.5M	Management System 4	10.499	tons/ha	3
IFSAR 2.5M	Management System 1	10.500	tons/ha	4
IFSAR 2.5M	Management System 5	11.242	tons/ha	5
IFSAR 2.5M	Management System 3	12.198	tons/ha	6
IFSAR 10M	Management System 6	3.978	tons/ha	1
IFSAR 10M	Management System 1	4.926	tons/ha	2
IFSAR 10M	Management System 2	5.919	tons/ha	3
IFSAR 10M	Management System 5	6.509	tons/ha	4
IFSAR 10M	Management System 4	7.442	tons/ha	5
IFSAR 10M	Management System 3	8.767	tons/ha	6
USGS 10M	Management System 6	1.907	tons/ha	1
USGS 10M	Management System 1	2.567	tons/ha	2
USGS 10M	Management System 2	2.761	tons/ha	3
USGS 10M	Management System 5	2.840	tons/ha	4
USGS 10M	Management System 3	3.614	tons/ha	5
USGS 10M	Management System 4	3.641	tons/ha	6
USGS 30M	Management System 6	1.636	tons/ha	1
USGS 30M	Management System 5	3.013	tons/ha	2
USGS 30M	Management System 2	3.139	tons/ha	3
USGS 30M	Management System 1	3.437	tons/ha	4
USGS 30M	Management System 3	4.336	tons/ha	5
USGS 30M	Management System 4	4.419	tons/ha	6
WG 10M	Management System 6	2.529	tons/ha	1
WG 10M	Management System 1	3.811	tons/ha	2
WG 10M	Management System 5	4.496	tons/ha	3
WG 10M	Management System 2	4.984	tons/ha	4
WG 10M	Management System 4	6.766	tons/ha	5
WG 10M	Management System 3	7.263	tons/ha	6

Table I.3. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 1.5% contributing source area and a 10 year return period, 30 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 5	12.18	tons/ha	1
IFSAR 2.5M	Management System 3	14.18	tons/ha	2
IFSAR 2.5M	Management System 2	19.40	tons/ha	3
IFSAR 2.5M	Management System 6	21.03	tons/ha	4
IFSAR 2.5M	Management System 1	27.77	tons/ha	5
IFSAR 2.5M	Management System 4	29.43	tons/ha	6
IFSAR 10M	Management System 6	8.99	tons/ha	1
IFSAR 10M	Management System 3	11.45	tons/ha	2
IFSAR 10M	Management System 4	11.83	tons/ha	3
IFSAR 10M	Management System 5	12.62	tons/ha	4
IFSAR 10M	Management System 1	13.73	tons/ha	5
IFSAR 10M	Management System 2	14.73	tons/ha	6
USGS 10M	Management System 2	5.37	tons/ha	1
USGS 10M	Management System 6	6.33	tons/ha	2
USGS 10M	Management System 3	6.61	tons/ha	3
USGS 10M	Management System 5	6.76	tons/ha	4
USGS 10M	Management System 1	8.21	tons/ha	5
USGS 10M	Management System 4	8.43	tons/ha	6
USGS 30M	Management System 2	3.94	tons/ha	1
USGS 30M	Management System 5	7.32	tons/ha	2
USGS 30M	Management System 6	7.90	tons/ha	3
USGS 30M	Management System 3	8.05	tons/ha	4
USGS 30M	Management System 4	9.69	tons/ha	5
USGS 30M	Management System 1	10.59	tons/ha	6
WG 10M	Management System 5	7.81	tons/ha	1
WG 10M	Management System 6	7.95	tons/ha	2
WG 10M	Management System 3	8.25	tons/ha	3
WG 10M	Management System 2	8.61	tons/ha	4
WG 10M	Management System 1	9.12	tons/ha	5
WG 10M	Management System 4	9.60	tons/ha	6

Table I.4. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 1.5% contributing source area and a 10 year return period, 60 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 4	37.074	tons/ha	1
IFSAR 2.5M	Management System 6	42.398	tons/ha	2
IFSAR 2.5M	Management System 3	43.350	tons/ha	3
IFSAR 2.5M	Management System 5	44.495	tons/ha	4
IFSAR 2.5M	Management System 1	47.399	tons/ha	5
IFSAR 2.5M	Management System 2	50.510	tons/ha	6
IFSAR 10M	Management System 2	23.190	tons/ha	1
IFSAR 10M	Management System 6	24.601	tons/ha	2
IFSAR 10M	Management System 1	26.233	tons/ha	3
IFSAR 10M	Management System 4	27.173	tons/ha	4
IFSAR 10M	Management System 5	28.343	tons/ha	5
IFSAR 10M	Management System 3	30.745	tons/ha	6
USGS 10M	Management System 6	8.751	tons/ha	1
USGS 10M	Management System 1	8.876	tons/ha	2
USGS 10M	Management System 2	9.956	tons/ha	3
USGS 10M	Management System 4	12.203	tons/ha	4
USGS 10M	Management System 3	13.708	tons/ha	5
USGS 10M	Management System 5	14.956	tons/ha	6
USGS 30M	Management System 6	7.305	tons/ha	1
USGS 30M	Management System 4	10.458	tons/ha	2
USGS 30M	Management System 1	11.664	tons/ha	3
USGS 30M	Management System 5	11.869	tons/ha	4
USGS 30M	Management System 3	12.768	tons/ha	5
USGS 30M	Management System 2	13.276	tons/ha	6
WG 10M	Management System 2	14.518	tons/ha	1
WG 10M	Management System 6	17.867	tons/ha	2
WG 10M	Management System 1	17.980	tons/ha	3
WG 10M	Management System 3	18.313	tons/ha	4
WG 10M	Management System 4	21.643	tons/ha	5
WG 10M	Management System 5	22.329	tons/ha	6

Table I.5. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 1.5% contributing source area and a 100 year return period, 30 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 6	41.618	tons/ha	1
IFSAR 2.5M	Management System 2	50.061	tons/ha	2
IFSAR 2.5M	Management System 1	50.657	tons/ha	3
IFSAR 2.5M	Management System 4	51.976	tons/ha	4
IFSAR 2.5M	Management System 5	53.469	tons/ha	5
IFSAR 2.5M	Management System 3	55.757	tons/ha	6
IFSAR 10M	Management System 5	35.076	tons/ha	1
IFSAR 10M	Management System 3	36.415	tons/ha	2
IFSAR 10M	Management System 1	42.586	tons/ha	3
IFSAR 10M	Management System 4	44.022	tons/ha	4
IFSAR 10M	Management System 2	49.613	tons/ha	5
IFSAR 10M	Management System 6	54.442	tons/ha	6
USGS 10M	Management System 2	23.852	tons/ha	1
USGS 10M	Management System 5	26.018	tons/ha	2
USGS 10M	Management System 3	26.647	tons/ha	3
USGS 10M	Management System 1	27.089	tons/ha	4
USGS 10M	Management System 6	28.468	tons/ha	5
USGS 10M	Management System 4	33.705	tons/ha	6
USGS 30M	Management System 6	20.587	tons/ha	1
USGS 30M	Management System 1	21.276	tons/ha	2
USGS 30M	Management System 4	23.249	tons/ha	3
USGS 30M	Management System 5	30.428	tons/ha	4
USGS 30M	Management System 2	31.588	tons/ha	5
USGS 30M	Management System 3	33.548	tons/ha	6
WG 10M	Management System 1	31.190	tons/ha	1
WG 10M	Management System 6	33.065	tons/ha	2
WG 10M	Management System 4	38.627	tons/ha	3
WG 10M	Management System 2	40.302	tons/ha	4
WG 10M	Management System 3	41.697	tons/ha	5
WG 10M	Management System 5	42.322	tons/ha	6

Table I.6. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 1.5% contributing source area and a 100 year return period, 60 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 6	87.570	tons/ha	1
IFSAR 2.5M	Management System 4	96.102	tons/ha	2
IFSAR 2.5M	Management System 3	96.837	tons/ha	3
IFSAR 2.5M	Management System 5	100.249	tons/ha	4
IFSAR 2.5M	Management System 2	109.285	tons/ha	5
IFSAR 2.5M	Management System 1	124.325	tons/ha	6
IFSAR 10M	Management System 6	67.686	tons/ha	1
IFSAR 10M	Management System 5	71.614	tons/ha	2
IFSAR 10M	Management System 1	74.436	tons/ha	3
IFSAR 10M	Management System 3	84.789	tons/ha	4
IFSAR 10M	Management System 2	88.375	tons/ha	5
IFSAR 10M	Management System 4	92.431	tons/ha	6
USGS 10M	Management System 2	37.798	tons/ha	1
USGS 10M	Management System 3	37.824	tons/ha	2
USGS 10M	Management System 6	40.701	tons/ha	3
USGS 10M	Management System 1	41.003	tons/ha	4
USGS 10M	Management System 5	44.133	tons/ha	5
USGS 10M	Management System 4	46.571	tons/ha	6
USGS 30M	Management System 6	23.262	tons/ha	1
USGS 30M	Management System 1	23.897	tons/ha	2
USGS 30M	Management System 4	26.761	tons/ha	3
USGS 30M	Management System 3	27.831	tons/ha	4
USGS 30M	Management System 2	28.995	tons/ha	5
USGS 30M	Management System 5	31.347	tons/ha	6
WG 10M	Management System 6	39.730	tons/ha	1
WG 10M	Management System 3	46.231	tons/ha	2
WG 10M	Management System 5	48.665	tons/ha	3
WG 10M	Management System 4	50.783	tons/ha	4
WG 10M	Management System 2	53.877	tons/ha	5
WG 10M	Management System 1	55.107	tons/ha	6

Table I.7. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 8% contributing source area and a 5 year return period, 30 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 6	0.542	tons/ha	1
IFSAR 2.5M	Management System 2	0.767	tons/ha	2
IFSAR 2.5M	Management System 1	0.857	tons/ha	3
IFSAR 2.5M	Management System 4	0.913	tons/ha	4
IFSAR 2.5M	Management System 3	1.073	tons/ha	5
IFSAR 2.5M	Management System 5	1.115	tons/ha	6
IFSAR 10M	Management System 1	0.115	tons/ha	1
IFSAR 10M	Management System 6	0.174	tons/ha	2
IFSAR 10M	Management System 5	0.203	tons/ha	3
IFSAR 10M	Management System 2	0.242	tons/ha	4
IFSAR 10M	Management System 3	0.266	tons/ha	5
IFSAR 10M	Management System 4	0.328	tons/ha	6
USGS 10M	Management System 6	0.028	tons/ha	1
USGS 10M	Management System 2	0.039	tons/ha	2
USGS 10M	Management System 1	0.051	tons/ha	3
USGS 10M	Management System 4	0.059	tons/ha	4
USGS 10M	Management System 5	0.086	tons/ha	5
USGS 10M	Management System 3	0.094	tons/ha	6
USGS 30M	Management System 6	0.037	tons/ha	1
USGS 30M	Management System 2	0.054	tons/ha	2
USGS 30M	Management System 1	0.063	tons/ha	3
USGS 30M	Management System 4	0.072	tons/ha	4
USGS 30M	Management System 5	0.082	tons/ha	5
USGS 30M	Management System 3	0.090	tons/ha	6
WG 10M	Management System 6	0.079	tons/ha	1
WG 10M	Management System 5	0.096	tons/ha	2
WG 10M	Management System 1	0.124	tons/ha	3
WG 10M	Management System 2	0.125	tons/ha	4
WG 10M	Management System 3	0.131	tons/ha	5
WG 10M	Management System 4	0.176	tons/ha	6
SRTM 90M	Management System 6	0.019	tons/ha	1
SRTM 90M	Management System 2	0.019	tons/ha	2
SRTM 90M	Management System 1	0.023	tons/ha	3
SRTM 90M	Management System 4	0.035	tons/ha	4
SRTM 90M	Management System 3	0.076	tons/ha	5
SRTM 90M	Management System 5	0.097	tons/ha	6

Table I.8. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 8% contributing source area and a 5 year return period, 60 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 6	2.873	tons/ha	1
IFSAR 2.5M	Management System 2	3.422	tons/ha	2
IFSAR 2.5M	Management System 1	4.167	tons/ha	3
IFSAR 2.5M	Management System 5	4.522	tons/ha	4
IFSAR 2.5M	Management System 4	4.538	tons/ha	5
IFSAR 2.5M	Management System 3	4.905	tons/ha	6
IFSAR 10M	Management System 6	1.868	tons/ha	1
IFSAR 10M	Management System 2	2.171	tons/ha	2
IFSAR 10M	Management System 1	2.671	tons/ha	3
IFSAR 10M	Management System 5	2.886	tons/ha	4
IFSAR 10M	Management System 4	2.918	tons/ha	5
IFSAR 10M	Management System 3	3.139	tons/ha	6
USGS 10M	Management System 6	0.954	tons/ha	1
USGS 10M	Management System 2	1.162	tons/ha	2
USGS 10M	Management System 1	1.370	tons/ha	3
USGS 10M	Management System 4	1.501	tons/ha	4
USGS 10M	Management System 5	1.534	tons/ha	5
USGS 10M	Management System 3	1.678	tons/ha	6
USGS 30M	Management System 6	0.799	tons/ha	1
USGS 30M	Management System 2	0.984	tons/ha	2
USGS 30M	Management System 1	1.194	tons/ha	3
USGS 30M	Management System 4	1.320	tons/ha	4
USGS 30M	Management System 5	1.360	tons/ha	5
USGS 30M	Management System 3	1.489	tons/ha	6
WG 10M	Management System 6	1.384	tons/ha	1
WG 10M	Management System 2	1.648	tons/ha	2
WG 10M	Management System 1	1.948	tons/ha	3
WG 10M	Management System 4	2.152	tons/ha	4
WG 10M	Management System 5	2.153	tons/ha	5
WG 10M	Management System 3	2.310	tons/ha	6
SRTM 90M	Management System 6	0.180	tons/ha	1
SRTM 90M	Management System 2	0.237	tons/ha	2
SRTM 90M	Management System 1	0.277	tons/ha	3
SRTM 90M	Management System 4	0.305	tons/ha	4
SRTM 90M	Management System 5	0.315	tons/ha	5
SRTM 90M	Management System 3	0.354	tons/ha	6

Table I.9. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 8% contributing source area and a 10 year return period, 30 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 5	5.437	tons/ha	1
IFSAR 2.5M	Management System 2	9.336	tons/ha	2
IFSAR 2.5M	Management System 1	9.407	tons/ha	3
IFSAR 2.5M	Management System 6	10.604	tons/ha	4
IFSAR 2.5M	Management System 4	11.386	tons/ha	5
IFSAR 2.5M	Management System 3	11.408	tons/ha	6
IFSAR 10M	Management System 2	2.823	tons/ha	1
IFSAR 10M	Management System 6	5.894	tons/ha	2
IFSAR 10M	Management System 3	7.910	tons/ha	3
IFSAR 10M	Management System 1	8.089	tons/ha	4
IFSAR 10M	Management System 5	8.599	tons/ha	5
IFSAR 10M	Management System 4	8.605	tons/ha	6
USGS 10M	Management System 6	1.970	tons/ha	1
USGS 10M	Management System 4	2.077	tons/ha	2
USGS 10M	Management System 5	2.121	tons/ha	3
USGS 10M	Management System 3	2.258	tons/ha	4
USGS 10M	Management System 2	2.486	tons/ha	5
USGS 10M	Management System 1	3.215	tons/ha	6
USGS 30M	Management System 2	1.663	tons/ha	1
USGS 30M	Management System 4	1.981	tons/ha	2
USGS 30M	Management System 5	2.044	tons/ha	3
USGS 30M	Management System 3	2.175	tons/ha	4
USGS 30M	Management System 1	2.407	tons/ha	5
USGS 30M	Management System 6	2.514	tons/ha	6
WG 10M	Management System 6	3.619	tons/ha	1
WG 10M	Management System 4	3.995	tons/ha	2
WG 10M	Management System 2	4.265	tons/ha	3
WG 10M	Management System 1	6.618	tons/ha	4
WG 10M	Management System 3	6.689	tons/ha	5
WG 10M	Management System 5	9.487	tons/ha	6
SRTM 90M	Management System 2	0.321	tons/ha	1
SRTM 90M	Management System 1	0.361	tons/ha	2
SRTM 90M	Management System 5	0.395	tons/ha	3
SRTM 90M	Management System 3	0.420	tons/ha	4
SRTM 90M	Management System 4	0.523	tons/ha	5
SRTM 90M	Management System 6	1.191	tons/ha	6

Table I.10. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 8% contributing source area and a 10 year return period, 60 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 6	8.259	tons/ha	1
IFSAR 2.5M	Management System 2	9.149	tons/ha	2
IFSAR 2.5M	Management System 4	10.968	tons/ha	3
IFSAR 2.5M	Management System 3	22.883	tons/ha	4
IFSAR 2.5M	Management System 5	23.020	tons/ha	5
IFSAR 2.5M	Management System 1	30.971	tons/ha	6
IFSAR 10M	Management System 6	5.386	tons/ha	1
IFSAR 10M	Management System 4	7.157	tons/ha	2
IFSAR 10M	Management System 2	8.528	tons/ha	3
IFSAR 10M	Management System 5	12.030	tons/ha	4
IFSAR 10M	Management System 1	14.788	tons/ha	5
IFSAR 10M	Management System 3	15.538	tons/ha	6
USGS 10M	Management System 6	3.996	tons/ha	1
USGS 10M	Management System 1	5.010	tons/ha	2
USGS 10M	Management System 2	6.898	tons/ha	3
USGS 10M	Management System 5	7.300	tons/ha	4
USGS 10M	Management System 3	7.408	tons/ha	5
USGS 10M	Management System 4	8.239	tons/ha	6
USGS 30M	Management System 1	3.805	tons/ha	1
USGS 30M	Management System 6	3.806	tons/ha	2
USGS 30M	Management System 4	5.062	tons/ha	3
USGS 30M	Management System 2	5.478	tons/ha	4
USGS 30M	Management System 5	5.525	tons/ha	5
USGS 30M	Management System 3	5.675	tons/ha	6
WG 10M	Management System 4	5.262	tons/ha	1
WG 10M	Management System 2	6.294	tons/ha	2
WG 10M	Management System 5	7.407	tons/ha	3
WG 10M	Management System 3	7.681	tons/ha	4
WG 10M	Management System 1	9.094	tons/ha	5
WG 10M	Management System 6	10.440	tons/ha	6
SRTM 90M	Management System 6	0.615	tons/ha	1
SRTM 90M	Management System 2	0.692	tons/ha	2
SRTM 90M	Management System 1	0.771	tons/ha	3
SRTM 90M	Management System 4	0.814	tons/ha	4
SRTM 90M	Management System 5	0.838	tons/ha	5
SRTM 90M	Management System 3	0.878	tons/ha	6

Table I.11. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 8% contributing source area and a 100 year return period, 30 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 2	21.678	tons/ha	1
IFSAR 2.5M	Management System 4	24.499	tons/ha	2
IFSAR 2.5M	Management System 6	31.818	tons/ha	3
IFSAR 2.5M	Management System 1	46.227	tons/ha	4
IFSAR 2.5M	Management System 3	49.314	tons/ha	5
IFSAR 2.5M	Management System 5	62.867	tons/ha	6
IFSAR 10M	Management System 5	16.153	tons/ha	1
IFSAR 10M	Management System 3	23.406	tons/ha	2
IFSAR 10M	Management System 1	23.476	tons/ha	3
IFSAR 10M	Management System 4	24.022	tons/ha	4
IFSAR 10M	Management System 6	26.792	tons/ha	5
IFSAR 10M	Management System 2	34.801	tons/ha	6
USGS 10M	Management System 1	9.482	tons/ha	1
USGS 10M	Management System 5	9.963	tons/ha	2
USGS 10M	Management System 6	10.430	tons/ha	3
USGS 10M	Management System 2	14.164	tons/ha	4
USGS 10M	Management System 4	16.047	tons/ha	5
USGS 10M	Management System 3	16.352	tons/ha	6
USGS 30M	Management System 1	7.454	tons/ha	1
USGS 30M	Management System 5	7.897	tons/ha	2
USGS 30M	Management System 2	8.698	tons/ha	3
USGS 30M	Management System 4	9.625	tons/ha	4
USGS 30M	Management System 6	10.694	tons/ha	5
USGS 30M	Management System 3	11.178	tons/ha	6
WG 10M	Management System 2	13.832	tons/ha	1
WG 10M	Management System 1	14.971	tons/ha	2
WG 10M	Management System 4	15.394	tons/ha	3
WG 10M	Management System 6	17.396	tons/ha	4
WG 10M	Management System 3	18.453	tons/ha	5
WG 10M	Management System 5	20.855	tons/ha	6
SRTM 90M	Management System 5	2.538	tons/ha	1
SRTM 90M	Management System 3	2.605	tons/ha	2
SRTM 90M	Management System 6	4.165	tons/ha	3
SRTM 90M	Management System 2	4.808	tons/ha	4
SRTM 90M	Management System 1	4.900	tons/ha	5
SRTM 90M	Management System 4	5.162	tons/ha	6

Table I.12. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 8% contributing source area and a 100 year return period, 60 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 5	47.241	tons/ha	1
IFSAR 2.5M	Management System 4	56.822	tons/ha	2
IFSAR 2.5M	Management System 3	84.155	tons/ha	3
IFSAR 2.5M	Management System 6	85.704	tons/ha	4
IFSAR 2.5M	Management System 2	86.374	tons/ha	5
IFSAR 2.5M	Management System 1	94.406	tons/ha	6
IFSAR 10M	Management System 1	30.630	tons/ha	1
IFSAR 10M	Management System 6	37.281	tons/ha	2
IFSAR 10M	Management System 2	38.881	tons/ha	3
IFSAR 10M	Management System 4	42.426	tons/ha	4
IFSAR 10M	Management System 5	42.792	tons/ha	5
IFSAR 10M	Management System 3	43.151	tons/ha	6
USGS 10M	Management System 4	18.993	tons/ha	1
USGS 10M	Management System 5	19.330	tons/ha	2
USGS 10M	Management System 3	19.628	tons/ha	3
USGS 10M	Management System 1	21.316	tons/ha	4
USGS 10M	Management System 6	26.503	tons/ha	5
USGS 10M	Management System 2	26.912	tons/ha	6
USGS 30M	Management System 2	15.904	tons/ha	1
USGS 30M	Management System 1	16.933	tons/ha	2
USGS 30M	Management System 4	17.340	tons/ha	3
USGS 30M	Management System 6	19.874	tons/ha	4
USGS 30M	Management System 3	20.791	tons/ha	5
USGS 30M	Management System 5	25.651	tons/ha	6
WG 10M	Management System 3	23.569	tons/ha	1
WG 10M	Management System 2	26.694	tons/ha	2
WG 10M	Management System 1	28.359	tons/ha	3
WG 10M	Management System 6	31.805	tons/ha	4
WG 10M	Management System 5	34.280	tons/ha	5
WG 10M	Management System 4	44.343	tons/ha	6
SRTM 90M	Management System 5	4.212	tons/ha	1
SRTM 90M	Management System 3	4.287	tons/ha	2
SRTM 90M	Management System 6	8.256	tons/ha	3
SRTM 90M	Management System 2	9.058	tons/ha	4
SRTM 90M	Management System 1	9.370	tons/ha	5
SRTM 90M	Management System 4	9.660	tons/ha	6

Table I.13. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 15% contributing source area and a 5 year return period, 30 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 6	0.718	tons/ha	1
IFSAR 2.5M	Management System 1	1.017	tons/ha	2
IFSAR 2.5M	Management System 2	1.031	tons/ha	3
IFSAR 2.5M	Management System 4	1.076	tons/ha	4
IFSAR 2.5M	Management System 5	1.431	tons/ha	5
IFSAR 2.5M	Management System 3	1.649	tons/ha	6
IFSAR 10M	Management System 1	0.230	tons/ha	1
IFSAR 10M	Management System 6	0.268	tons/ha	2
IFSAR 10M	Management System 2	0.356	tons/ha	3
IFSAR 10M	Management System 4	0.463	tons/ha	4
IFSAR 10M	Management System 5	0.549	tons/ha	5
IFSAR 10M	Management System 3	0.595	tons/ha	6
USGS 10M	Management System 6	0.056	tons/ha	1
USGS 10M	Management System 4	0.077	tons/ha	2
USGS 10M	Management System 2	0.083	tons/ha	3
USGS 10M	Management System 1	0.099	tons/ha	4
USGS 10M	Management System 5	0.105	tons/ha	5
USGS 10M	Management System 3	0.147	tons/ha	6
USGS 30M	Management System 6	0.056	tons/ha	1
USGS 30M	Management System 2	0.069	tons/ha	2
USGS 30M	Management System 4	0.081	tons/ha	3
USGS 30M	Management System 1	0.096	tons/ha	4
USGS 30M	Management System 3	0.103	tons/ha	5
USGS 30M	Management System 5	0.139	tons/ha	6
WG 10M	Management System 3	0.127	tons/ha	1
WG 10M	Management System 6	0.131	tons/ha	2
WG 10M	Management System 1	0.158	tons/ha	3
WG 10M	Management System 2	0.210	tons/ha	4
WG 10M	Management System 5	0.221	tons/ha	5
WG 10M	Management System 4	0.243	tons/ha	6
SRTM 90M	Management System 1	0.014	tons/ha	1
SRTM 90M	Management System 6	0.016	tons/ha	2
SRTM 90M	Management System 2	0.021	tons/ha	3
SRTM 90M	Management System 4	0.025	tons/ha	4
SRTM 90M	Management System 3	0.071	tons/ha	5
SRTM 90M	Management System 5	0.071	tons/ha	6

Table I.14. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 15% contributing source area and a 5 year return period, 60 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 6	2.625	tons/ha	1
IFSAR 2.5M	Management System 2	3.207	tons/ha	2
IFSAR 2.5M	Management System 1	4.087	tons/ha	3
IFSAR 2.5M	Management System 4	4.352	tons/ha	4
IFSAR 2.5M	Management System 5	4.368	tons/ha	5
IFSAR 2.5M	Management System 3	4.619	tons/ha	6
IFSAR 10M	Management System 6	1.659	tons/ha	1
IFSAR 10M	Management System 2	2.012	tons/ha	2
IFSAR 10M	Management System 1	2.606	tons/ha	3
IFSAR 10M	Management System 5	2.744	tons/ha	4
IFSAR 10M	Management System 4	2.785	tons/ha	5
IFSAR 10M	Management System 3	2.943	tons/ha	6
USGS 10M	Management System 6	0.841	tons/ha	1
USGS 10M	Management System 1	1.281	tons/ha	2
USGS 10M	Management System 4	2.085	tons/ha	3
USGS 10M	Management System 2	2.450	tons/ha	4
USGS 10M	Management System 3	2.470	tons/ha	5
USGS 10M	Management System 5	3.392	tons/ha	6
USGS 30M	Management System 6	0.705	tons/ha	1
USGS 30M	Management System 5	2.170	tons/ha	2
USGS 30M	Management System 4	2.193	tons/ha	3
USGS 30M	Management System 2	2.447	tons/ha	4
USGS 30M	Management System 3	2.472	tons/ha	5
USGS 30M	Management System 1	2.584	tons/ha	6
WG 10M	Management System 6	1.226	tons/ha	1
WG 10M	Management System 2	1.492	tons/ha	2
WG 10M	Management System 4	2.053	tons/ha	3
WG 10M	Management System 3	2.173	tons/ha	4
WG 10M	Management System 1	3.533	tons/ha	5
WG 10M	Management System 5	3.827	tons/ha	6
SRTM 90M	Management System 6	0.183	tons/ha	1
SRTM 90M	Management System 2	0.241	tons/ha	2
SRTM 90M	Management System 1	0.297	tons/ha	3
SRTM 90M	Management System 4	0.696	tons/ha	4
SRTM 90M	Management System 3	0.716	tons/ha	5
SRTM 90M	Management System 5	0.737	tons/ha	6

Table I.15. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 15% contributing source area and a 10 year return period, 30 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 4	12.069	tons/ha	1
IFSAR 2.5M	Management System 5	12.418	tons/ha	2
IFSAR 2.5M	Management System 1	14.084	tons/ha	3
IFSAR 2.5M	Management System 2	18.305	tons/ha	4
IFSAR 2.5M	Management System 6	19.563	tons/ha	5
IFSAR 2.5M	Management System 3	21.364	tons/ha	6
IFSAR 10M	Management System 5	3.280	tons/ha	1
IFSAR 10M	Management System 3	5.450	tons/ha	2
IFSAR 10M	Management System 6	6.158	tons/ha	3
IFSAR 10M	Management System 1	6.180	tons/ha	4
IFSAR 10M	Management System 4	6.476	tons/ha	5
IFSAR 10M	Management System 2	6.894	tons/ha	6
USGS 10M	Management System 1	1.853	tons/ha	1
USGS 10M	Management System 4	1.910	tons/ha	2
USGS 10M	Management System 5	2.020	tons/ha	3
USGS 10M	Management System 3	2.090	tons/ha	4
USGS 10M	Management System 2	2.378	tons/ha	5
USGS 10M	Management System 6	2.448	tons/ha	6
USGS 30M	Management System 1	1.725	tons/ha	1
USGS 30M	Management System 4	1.811	tons/ha	2
USGS 30M	Management System 6	1.889	tons/ha	3
USGS 30M	Management System 5	1.907	tons/ha	4
USGS 30M	Management System 2	1.987	tons/ha	5
USGS 30M	Management System 3	1.998	tons/ha	6
WG 10M	Management System 1	3.692	tons/ha	1
WG 10M	Management System 4	3.990	tons/ha	2
WG 10M	Management System 2	4.388	tons/ha	3
WG 10M	Management System 5	5.457	tons/ha	4
WG 10M	Management System 3	5.693	tons/ha	5
WG 10M	Management System 6	7.018	tons/ha	6
SRTM 90M	Management System 1	0.380	tons/ha	1
SRTM 90M	Management System 5	0.417	tons/ha	2
SRTM 90M	Management System 3	0.428	tons/ha	3
SRTM 90M	Management System 4	0.575	tons/ha	4
SRTM 90M	Management System 2	0.733	tons/ha	5
SRTM 90M	Management System 6	1.131	tons/ha	6

Table I.16. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 15% contributing source area and a 10 year return period, 60 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 2	18.762	tons/ha	1
IFSAR 2.5M	Management System 1	21.251	tons/ha	2
IFSAR 2.5M	Management System 6	21.777	tons/ha	3
IFSAR 2.5M	Management System 4	21.813	tons/ha	4
IFSAR 2.5M	Management System 5	22.158	tons/ha	5
IFSAR 2.5M	Management System 3	22.516	tons/ha	6
IFSAR 10M	Management System 2	5.595	tons/ha	1
IFSAR 10M	Management System 4	6.898	tons/ha	2
IFSAR 10M	Management System 6	8.040	tons/ha	3
IFSAR 10M	Management System 5	8.898	tons/ha	4
IFSAR 10M	Management System 3	9.242	tons/ha	5
IFSAR 10M	Management System 1	11.905	tons/ha	6
USGS 10M	Management System 6	3.051	tons/ha	1
USGS 10M	Management System 2	3.414	tons/ha	2
USGS 10M	Management System 4	4.085	tons/ha	3
USGS 10M	Management System 1	5.017	tons/ha	4
USGS 10M	Management System 5	5.432	tons/ha	5
USGS 10M	Management System 3	5.652	tons/ha	6
USGS 30M	Management System 6	3.620	tons/ha	1
USGS 30M	Management System 1	3.665	tons/ha	2
USGS 30M	Management System 5	3.918	tons/ha	3
USGS 30M	Management System 3	4.081	tons/ha	4
USGS 30M	Management System 2	4.259	tons/ha	5
USGS 30M	Management System 4	4.954	tons/ha	6
WG 10M	Management System 4	5.123	tons/ha	1
WG 10M	Management System 2	6.275	tons/ha	2
WG 10M	Management System 6	7.517	tons/ha	3
WG 10M	Management System 5	7.544	tons/ha	4
WG 10M	Management System 3	7.734	tons/ha	5
WG 10M	Management System 1	9.623	tons/ha	6
SRTM 90M	Management System 2	0.704	tons/ha	1
SRTM 90M	Management System 1	0.811	tons/ha	2
SRTM 90M	Management System 4	0.828	tons/ha	3
SRTM 90M	Management System 5	0.874	tons/ha	4
SRTM 90M	Management System 3	0.896	tons/ha	5
SRTM 90M	Management System 6	1.070	tons/ha	6

Table I.17. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 15% contributing source area and a 100 year return period, 30 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 1	23.677	tons/ha	1
IFSAR 2.5M	Management System 5	24.203	tons/ha	2
IFSAR 2.5M	Management System 3	24.541	tons/ha	3
IFSAR 2.5M	Management System 4	31.775	tons/ha	4
IFSAR 2.5M	Management System 2	59.103	tons/ha	5
IFSAR 2.5M	Management System 6	59.458	tons/ha	6
IFSAR 10M	Management System 5	18.986	tons/ha	1
IFSAR 10M	Management System 3	19.418	tons/ha	2
IFSAR 10M	Management System 1	24.104	tons/ha	3
IFSAR 10M	Management System 4	27.572	tons/ha	4
IFSAR 10M	Management System 6	28.375	tons/ha	5
IFSAR 10M	Management System 2	32.579	tons/ha	6
USGS 10M	Management System 6	6.986	tons/ha	1
USGS 10M	Management System 2	7.504	tons/ha	2
USGS 10M	Management System 1	8.410	tons/ha	3
USGS 10M	Management System 4	8.554	tons/ha	4
USGS 10M	Management System 5	10.819	tons/ha	5
USGS 10M	Management System 3	11.062	tons/ha	6
USGS 30M	Management System 1	7.121	tons/ha	1
USGS 30M	Management System 6	7.523	tons/ha	2
USGS 30M	Management System 2	8.298	tons/ha	3
USGS 30M	Management System 4	9.312	tons/ha	4
USGS 30M	Management System 5	9.452	tons/ha	5
USGS 30M	Management System 3	9.727	tons/ha	6
WG 10M	Management System 5	11.972	tons/ha	1
WG 10M	Management System 3	12.204	tons/ha	2
WG 10M	Management System 6	13.186	tons/ha	3
WG 10M	Management System 2	14.042	tons/ha	4
WG 10M	Management System 1	15.553	tons/ha	5
WG 10M	Management System 4	15.868	tons/ha	6
SRTM 90M	Management System 5	2.846	tons/ha	1
SRTM 90M	Management System 3	2.900	tons/ha	2
SRTM 90M	Management System 6	4.476	tons/ha	3
SRTM 90M	Management System 2	5.213	tons/ha	4
SRTM 90M	Management System 1	5.441	tons/ha	5
SRTM 90M	Management System 4	5.693	tons/ha	6

Table I.18. Management system rankings using sediment yield predictions from Watershed 11 for simulations performed with a 15% contributing source area and a 100 year return period, 60 minute duration rainfall event.

DEM Name	Management System	Sediment Yield	Units	Ranking
IFSAR 2.5M	Management System 6	39.790	tons/ha	1
IFSAR 2.5M	Management System 2	41.828	tons/ha	2
IFSAR 2.5M	Management System 1	45.496	tons/ha	3
IFSAR 2.5M	Management System 4	46.132	tons/ha	4
IFSAR 2.5M	Management System 5	46.320	tons/ha	5
IFSAR 2.5M	Management System 3	46.652	tons/ha	6
IFSAR 10M	Management System 6	26.258	tons/ha	1
IFSAR 10M	Management System 2	27.725	tons/ha	2
IFSAR 10M	Management System 1	30.355	tons/ha	3
IFSAR 10M	Management System 5	30.737	tons/ha	4
IFSAR 10M	Management System 4	30.831	tons/ha	5
IFSAR 10M	Management System 3	31.106	tons/ha	6
USGS 10M	Management System 6	14.799	tons/ha	1
USGS 10M	Management System 2	15.648	tons/ha	2
USGS 10M	Management System 1	17.136	tons/ha	3
USGS 10M	Management System 4	17.340	tons/ha	4
USGS 10M	Management System 5	17.589	tons/ha	5
USGS 10M	Management System 3	17.767	tons/ha	6
USGS 30M	Management System 6	14.409	tons/ha	1
USGS 30M	Management System 2	15.353	tons/ha	2
USGS 30M	Management System 1	16.608	tons/ha	3
USGS 30M	Management System 4	16.888	tons/ha	4
USGS 30M	Management System 5	17.074	tons/ha	5
USGS 30M	Management System 3	17.333	tons/ha	6
WG 10M	Management System 5	23.597	tons/ha	1
WG 10M	Management System 3	23.841	tons/ha	2
WG 10M	Management System 6	25.483	tons/ha	3
WG 10M	Management System 2	27.101	tons/ha	4
WG 10M	Management System 1	29.170	tons/ha	5
WG 10M	Management System 4	34.998	tons/ha	6
SRTM 90M	Management System 5	4.580	tons/ha	1
SRTM 90M	Management System 3	4.625	tons/ha	2
SRTM 90M	Management System 6	9.154	tons/ha	3
SRTM 90M	Management System 2	10.054	tons/ha	4
SRTM 90M	Management System 1	10.486	tons/ha	5
SRTM 90M	Management System 4	10.744	tons/ha	6

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